A NUMERICAL STUDY ON THE SHEDDING FREQUENCY OF SHEET CAVITATION

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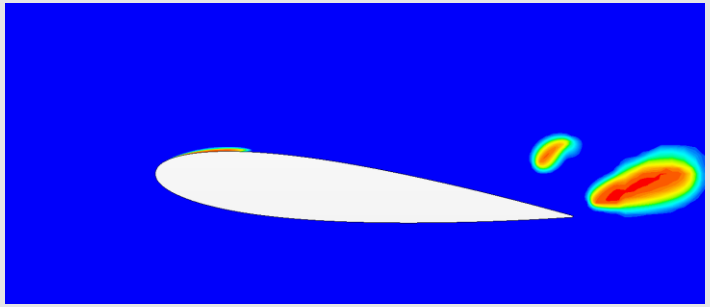
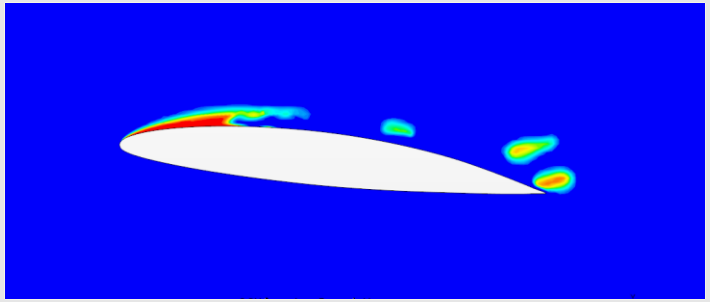
MARINE 2017

Research on the shedding frequency on two 2D hydrofoils

- The flow in span-wise direction is considered as a secondary flow
- Focus on the shedding frequency
- Verification study on the NACA0015 in 2D
    - Wetted Flow
    - Cavitating flow in 2 different cavitation numbers (σ=1, σ=1.6)
    - Assessment of uncertainty
- Implementation of the same procedure on the NACA66 and validation with experimental data.
- Good agreement with the experimental results was obtained, matching the shedding frequency





- Introduction
- Mathematical Model
- Case Description – NACA 0015
- Results – NACA 0015
- Case Description – NACA 66
- Results – NACA 66
- Conclusion

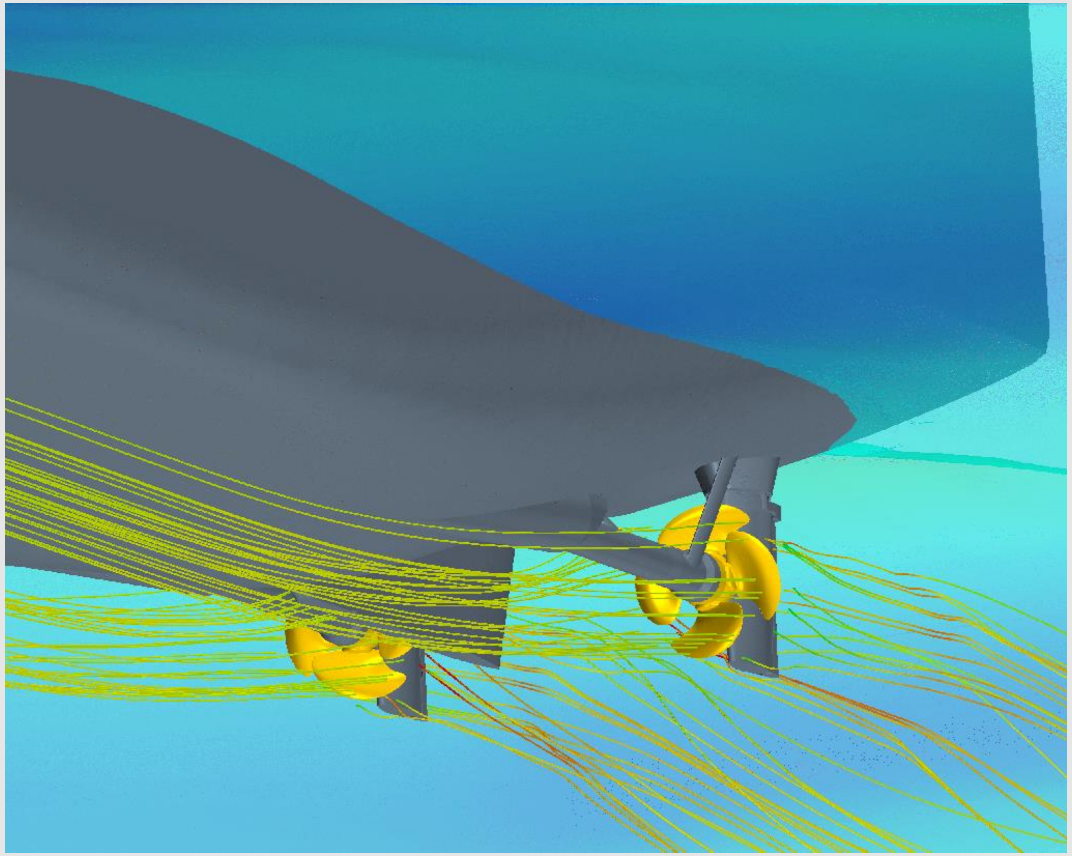
INTRODUCTION

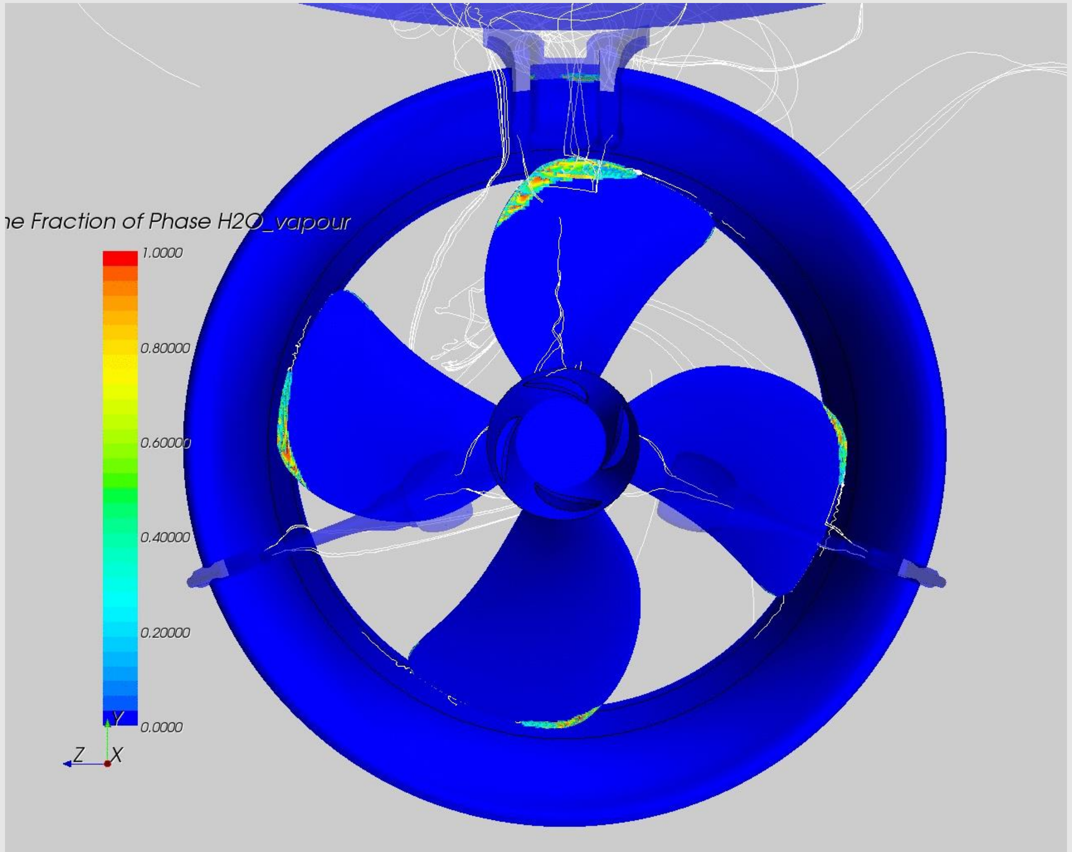
Cavitation in Maritime Industry

- Unavoidable and therefore accepted
- To which extent is it not harmful? (Noise? Erosion?)

“Simulation of Cavitation and Surface Erosion on Marine Propellers”

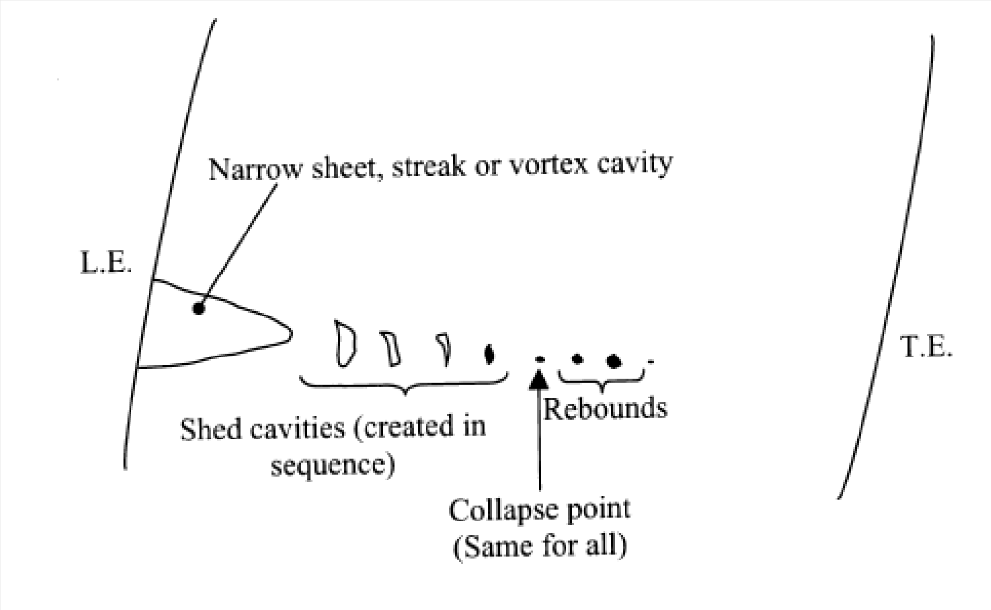
- Prediction of the time dependent development of the cavities on the propeller blades with the propeller in behind condition
- Erosion model for erosion risk assessment

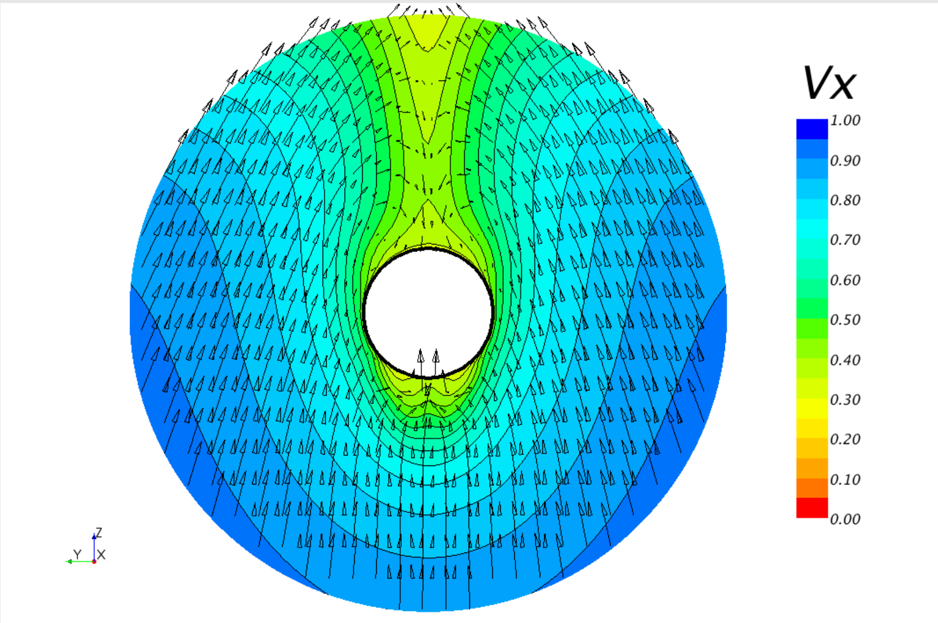




Propeller in behind condition

- The propeller blades suffer from two different phenomena:
  - Natural shedding frequency of the cavities
  - Wakefield (or blade pass) frequency



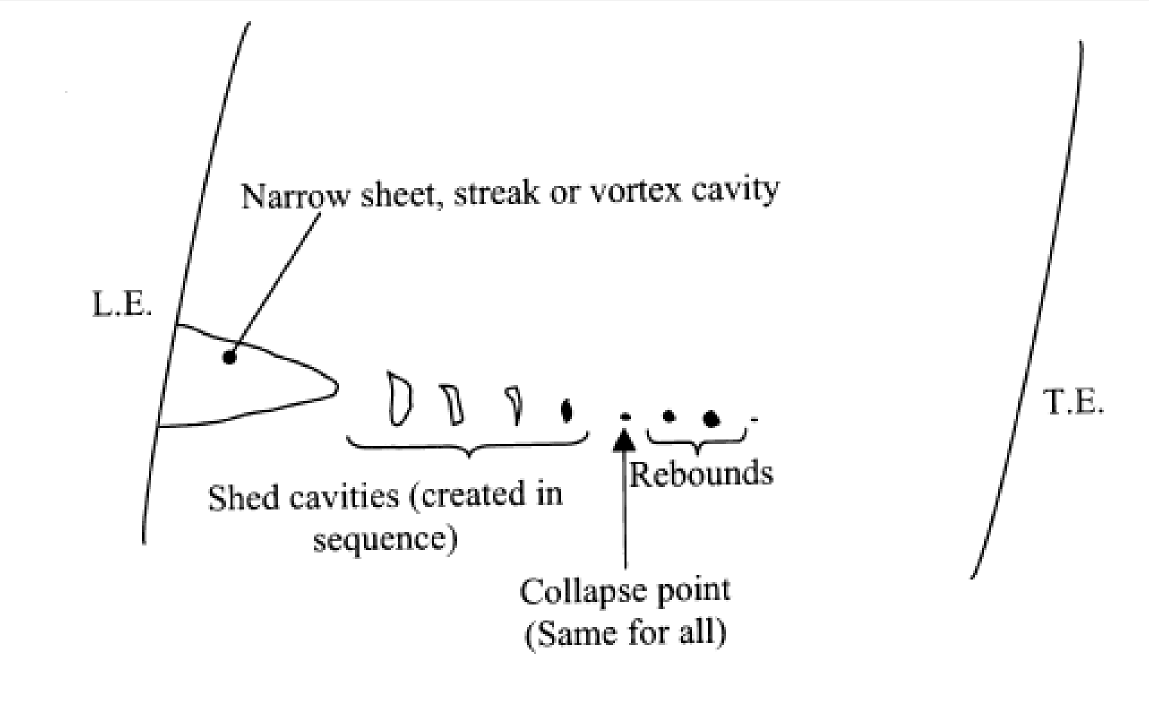


Shedding frequency of Sheet Cavitation

- **Sheet cavitation** may generate strong **shock waves**, originating from the collapse of the shed vapor structures, which then often **lead to erosion** of surface material

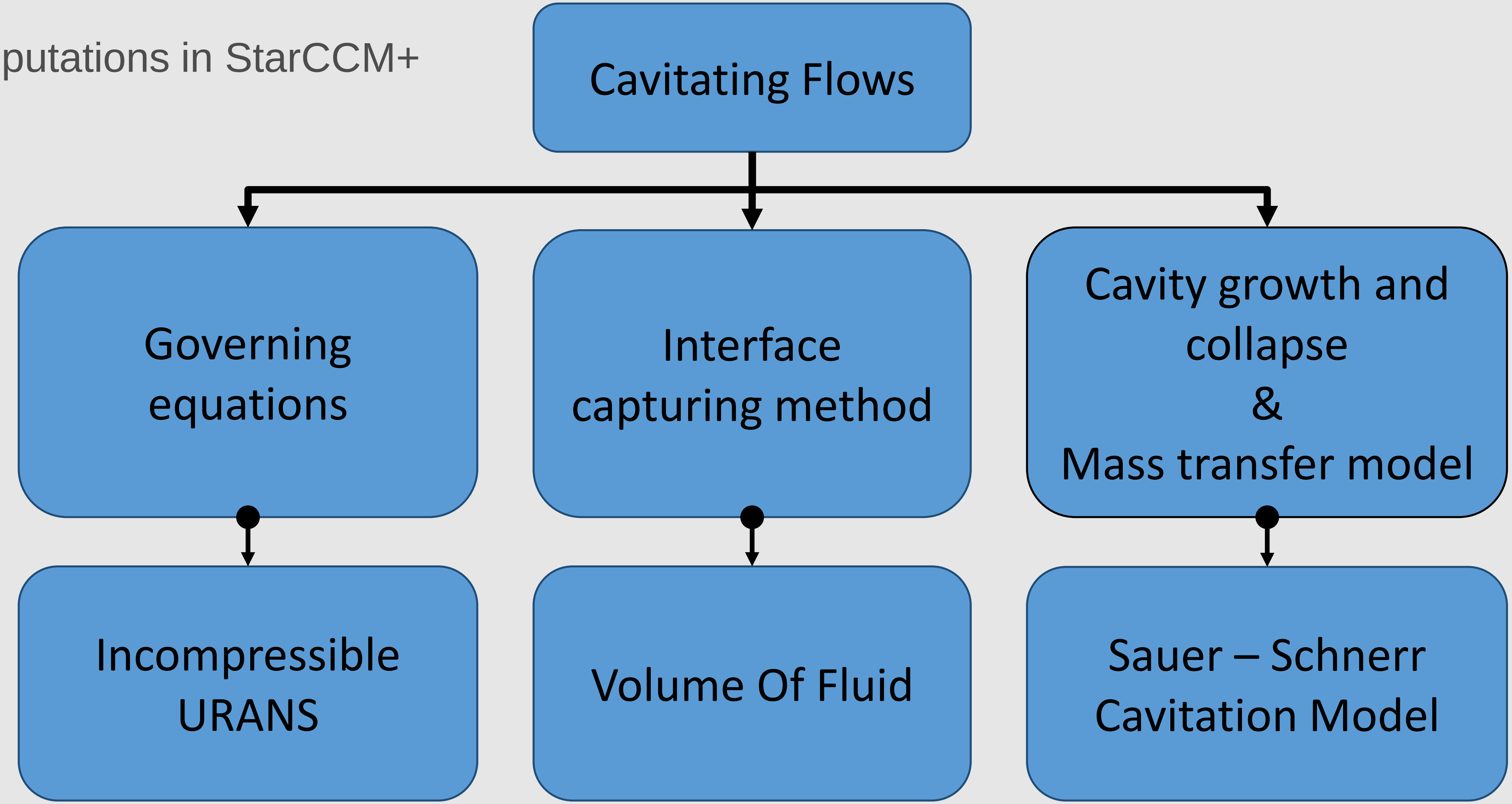
- Natural shedding frequency sometimes plays a role in cavitation erosion (Bark *et. al*.)

- The **shedding frequency** is numerically more sensitive and can be compared with experimental data



MATHEMATICAL MODELLING

- Computations in StarCCM+



[A Numerical Study on the Shedding Frequency of Sheet Cavitation / Melissaris, Bulten and Terwisga]

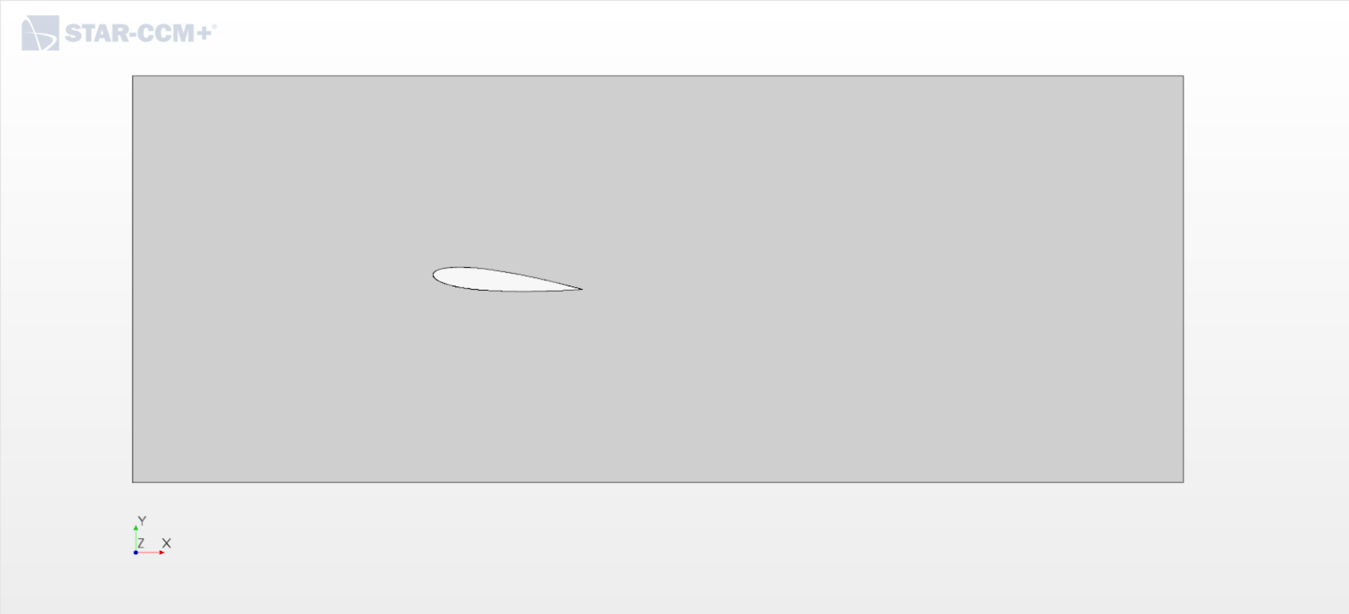
CASE DESCRIPTION

NACA 0015

WÄRTSILÄ

Computational Domain

- Chord length c=200 mm
- Angle of incidence 6 degrees
- Domain size 2 chord lengths ahead and 4 chord length downstream the trailing edge
- Vin = 6 m/s



Computational Mesh

- Unstructured mesh
- Trimmed cell mesh
- Prism layer mesh
- 4 Grids geometrically similar

Grid	# Cells	Max y+	Level
G1	25,059	1.2261	Coarse
G2	49,931	0.8407	Medium
G3	77,081	0.6808	Fine
G4	100,569	0.5829	Very fine

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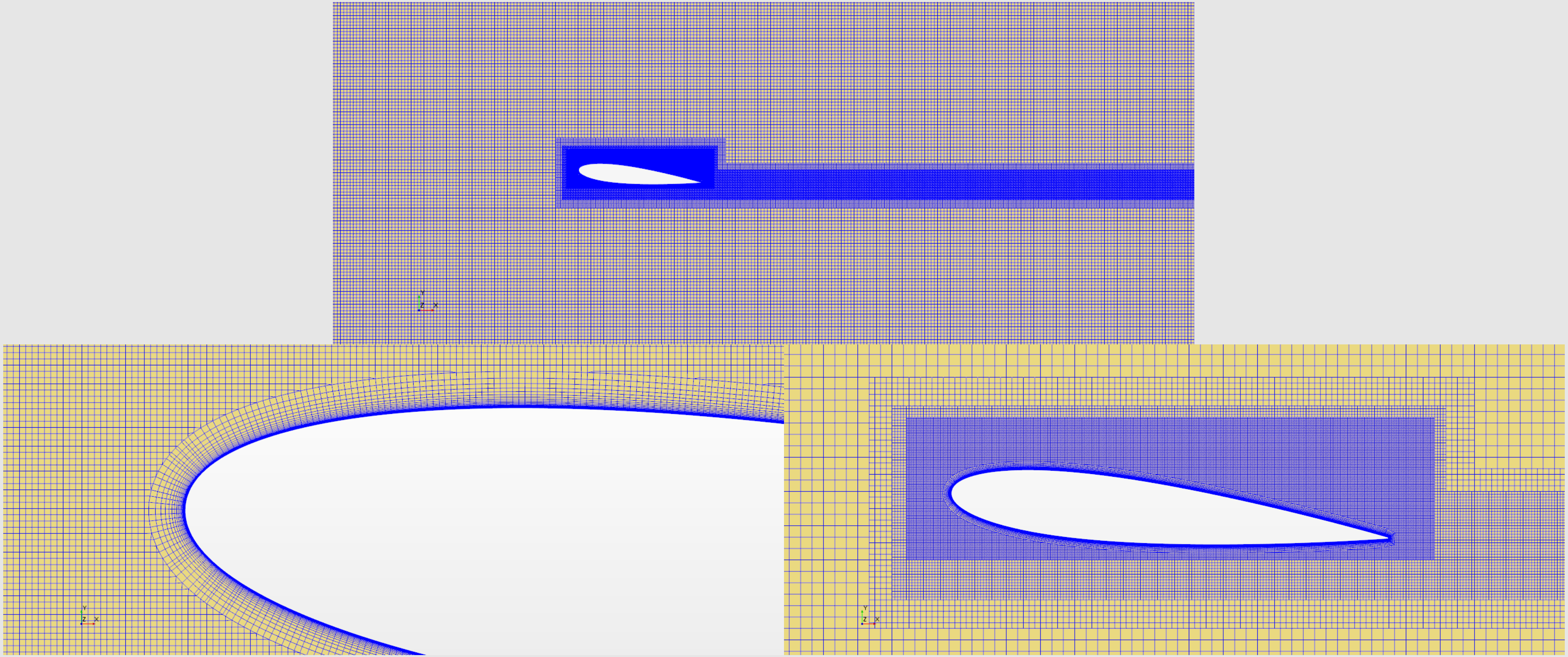
Very Fine Mesh Topology



Computational Setup

Boundary conditions	NACA0015 (AoA = 6°)	
Velocity Inlet	Vin = 6 m/s	
Pressure Outlet	Pout = 20.9 kPa (σ=1.0), 31.7 kPa (σ=1.6)	
Turbulent Intensity	1%	
Turbulent Viscosity Ratio	10	
Foil	No-slip Wall	
Top	Slip Wall	
Bottom	Slip Wall	
Fluid Properties	**Liquid**	**Vapor**
Density	ρ = 998 $\mathrm{kg/m^3}$	ρ = 0.023 $\mathrm{kg/m^3}$
Dynamic Viscosity	μ = 0.0011 kg/ms	μ = 9.95$\times 10^{-6}$ kg/ms
Saturation Pressure	p_v =2970 Pa	-

RESULTS NACA 0015

- ❑Wetted Flow
- ❑Cavitating Flow – Cavitation Number 1.6
- ❑Cavitating Flow – Cavitation Number 1.0

RESULTS NACA 0015

WETTED FLOW

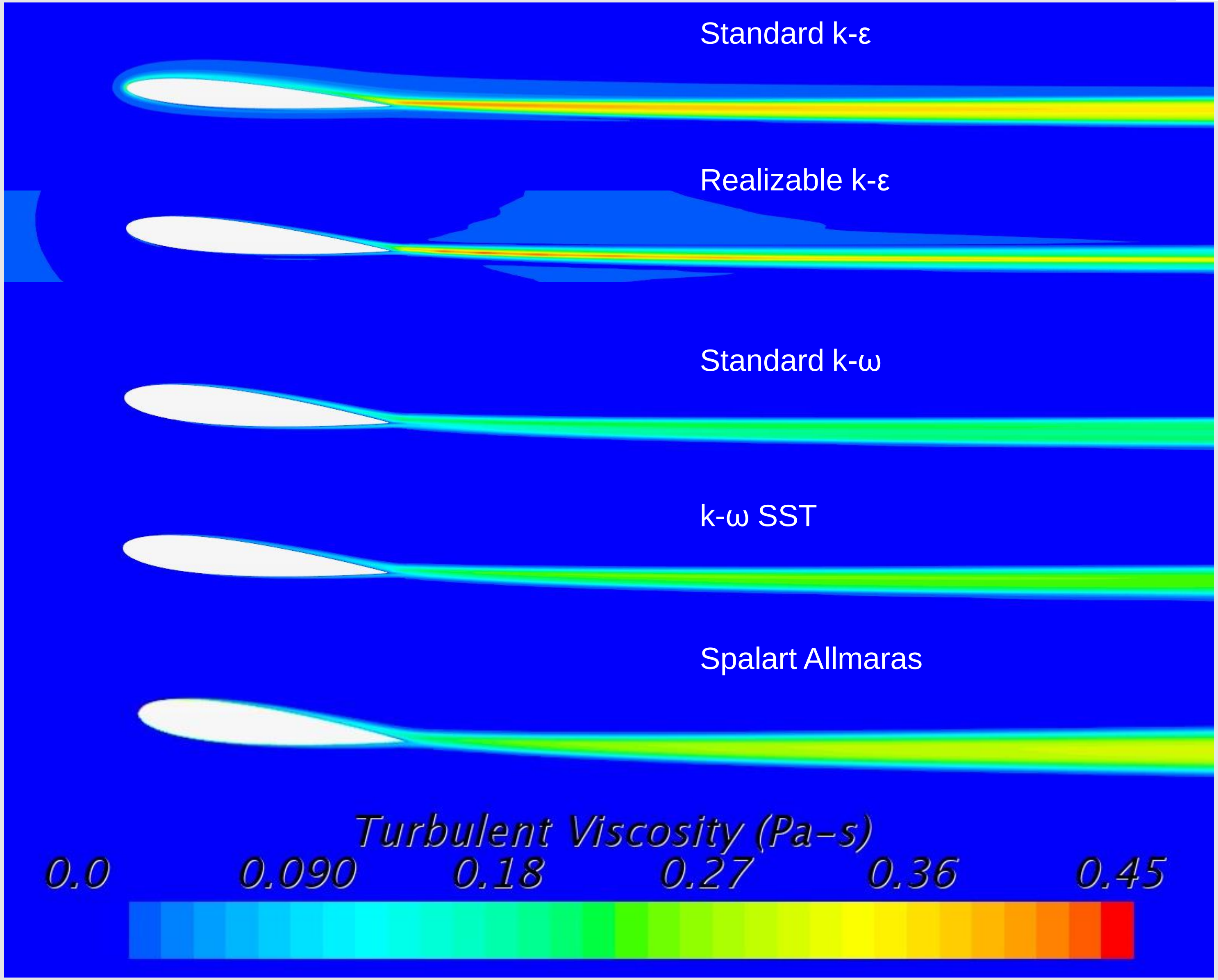
Turbulence Model Investigation

Comparison with Experimental data

Grid Sensitivity Study

Turbulent Viscosity

- Standard k-ε overpredicts the turbulent viscosity around the foil
- Similar turbulent viscosity pattern for the rest turbulence models
- Different maximum values



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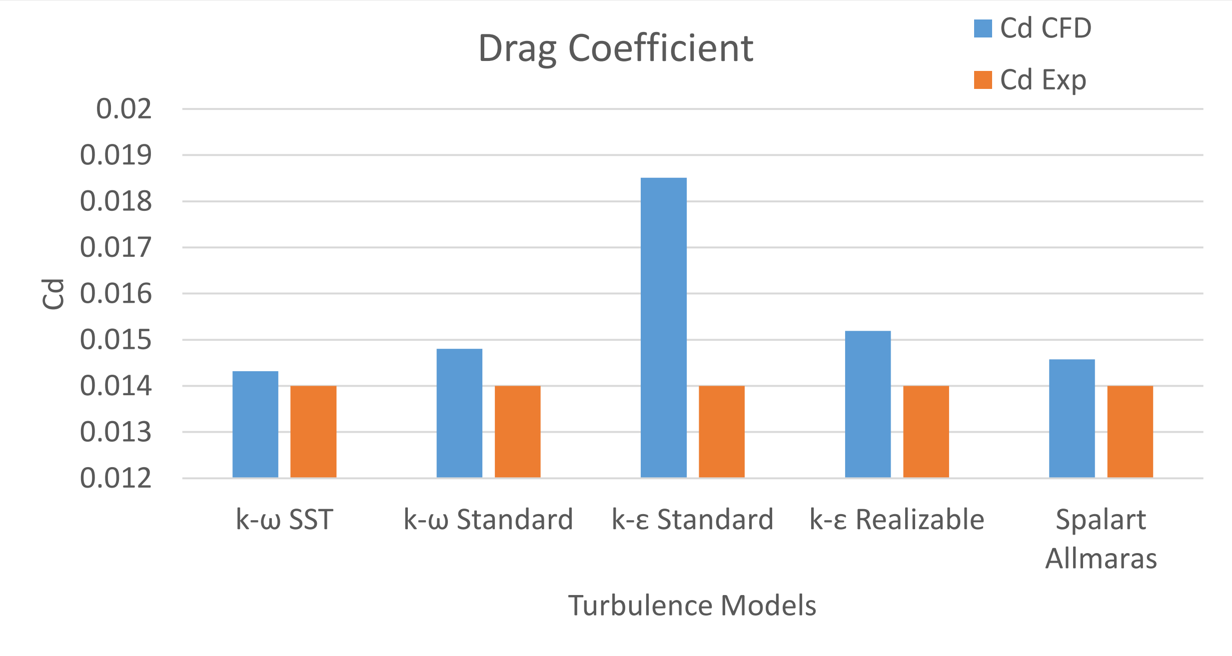
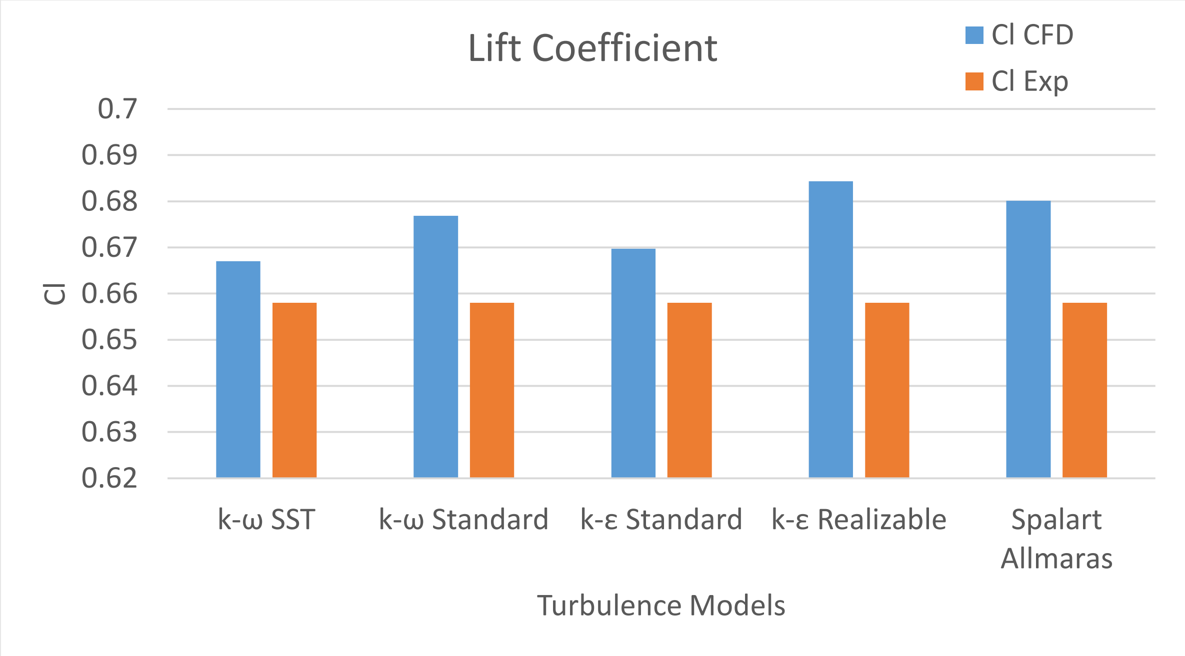
Results for different Turbulence Models

- Experimental values (VIRTUE)
  - $C_D = 0.014$
  - $C_L = 0.658$
  - $C_{p,stagnation} = 1$ (Analytical value)

Turbulence model	C_D	C_L	C_{p_min}	$C_{p_{stagnation}}$
k-ω SST	0.01432	0.66703	-2.05341	1.01123
Standard k-ω	0.01481	0.67689	-2.06686	1.01207
k-ε Standard	0.01851	0.66973	-2.03348	1.02306
k-ε Realizable	0.01519	0.68437	-2.07580	1.01289
k-ε Realizable	0.01457	0.68013	-2.07509	1.01319





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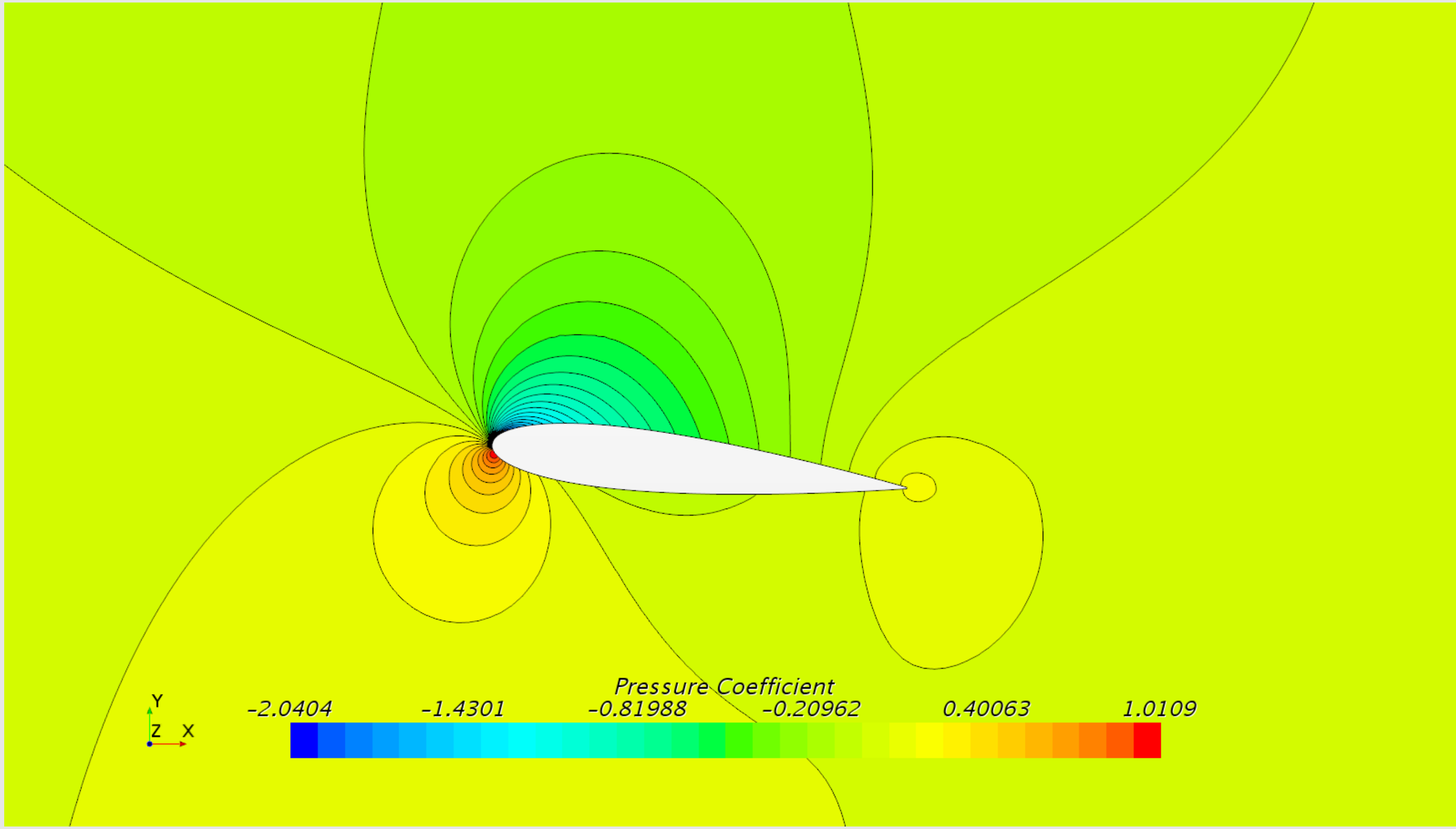
Pressure Distribution around the Foil

- K-ω SST turbulence model



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Results for different Grid Density

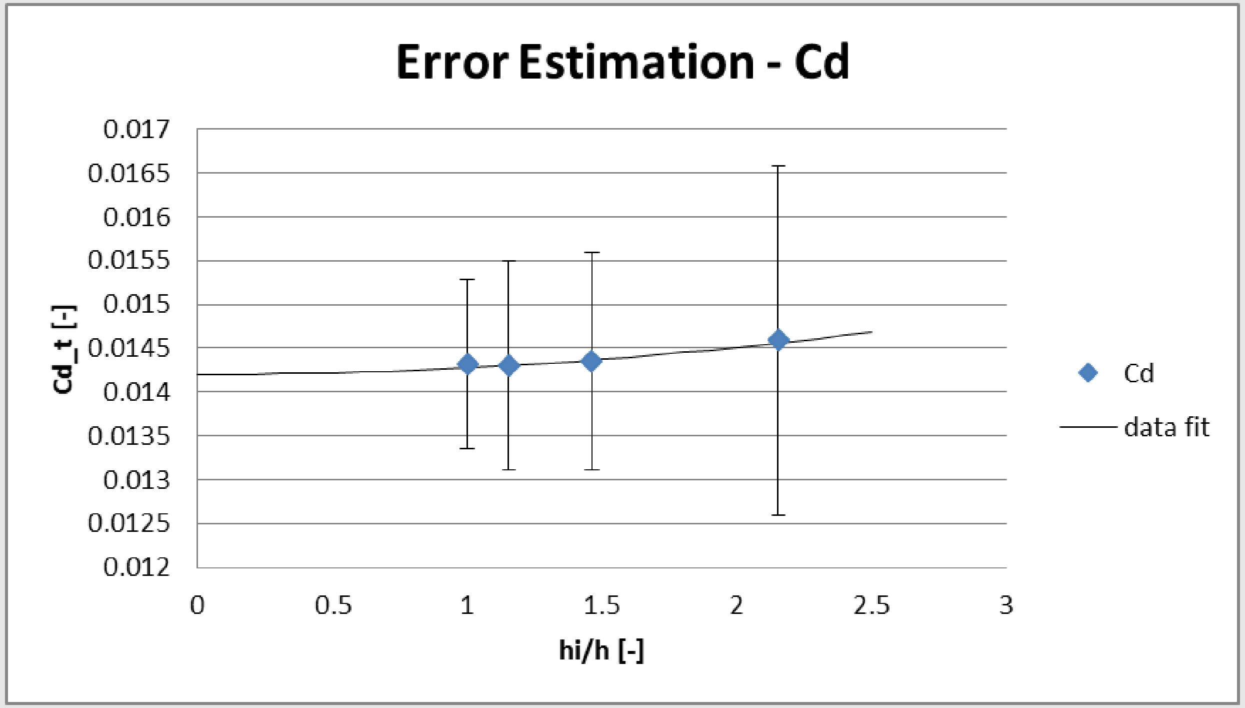
- Experimental Values:
  - $C_D = 0.014$
  - $C_L = 0.658$
  - $C_{p,stagnation} = 1$ (Analytical value)

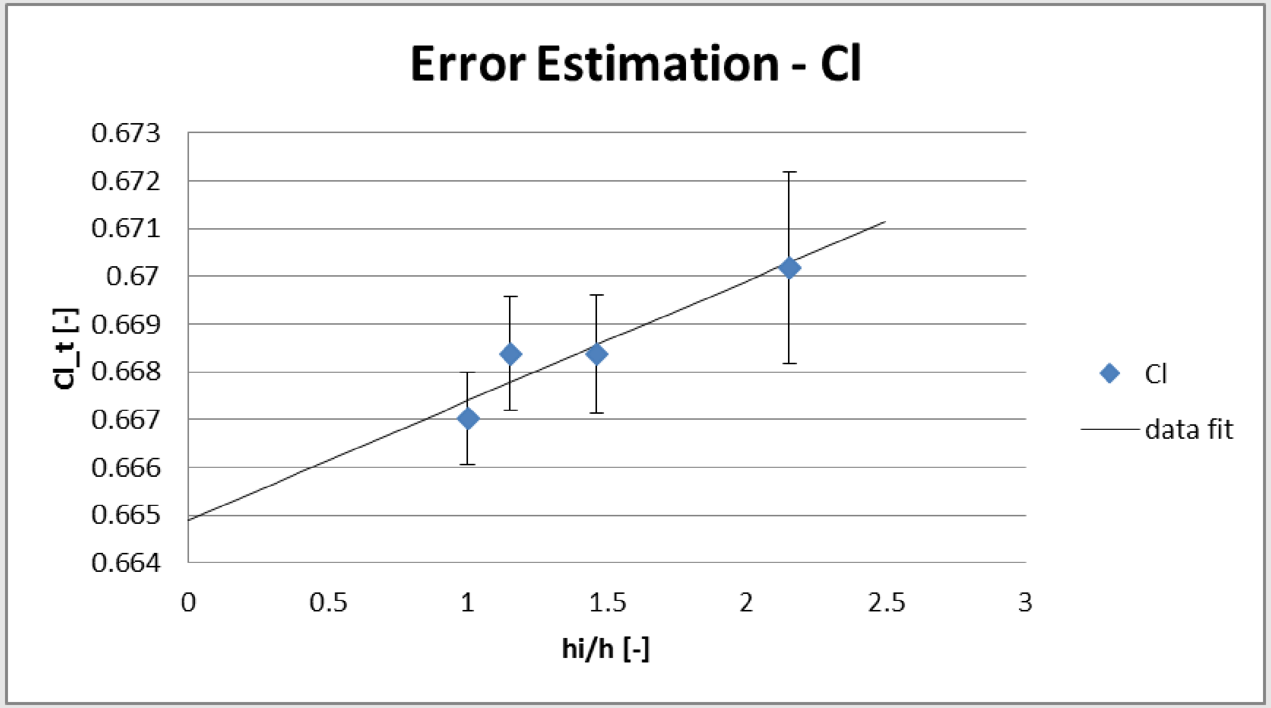
Grids	C_D	C_L	C_{p_min}	$C_{p_{stagnation}}$
G1	0.01459	0.67018	-2.05075	1.01275
G2	0.01435	0.66838	-2.05030	1.01187
G3	0.01430	0.66838	-2.04202	1.01110
G4	0.01432	0.66703	-2.05341	1.01123

Assessment of Uncertainty

- Error estimation with power series expansion (Eca and Hoekstra 2014)
- Expansions are fitted to the data in the least square sense

Mesh	Cd	Uncertainty	Cl	Uncertainty
Coarse	0.01459	8.47%	0.67018	2.40%
Medium	0.01435	3.48%	0.66838	1.62%
Fine	0.01430	2.36%	0.66838	1.69%
Very Fine	0.01432	3.05%	0.66703	1.05%





RESULTS – NACA 0015

CAVITATING FLOW

Cavitation Number 1.6

RESULTS – NACA 0015

Time Step Investigation

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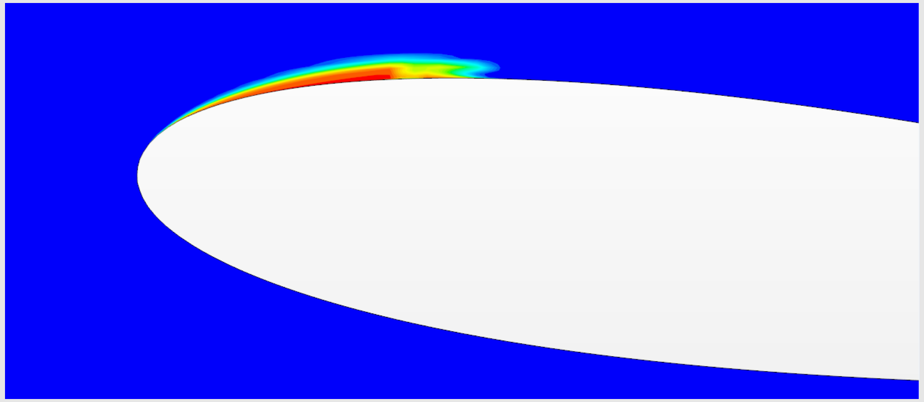
Inner Iterations Investigation

↓

Grid Sensitivity study

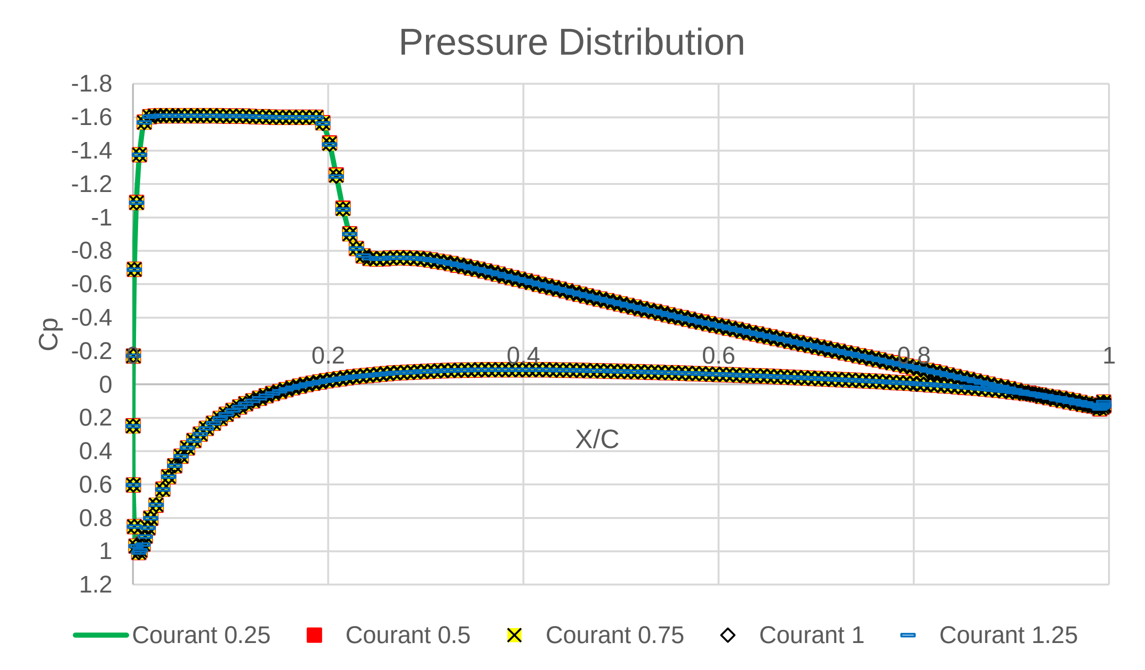
- Courant Number 0.75
- 5 Inner Iterations
- Coarse Mesh

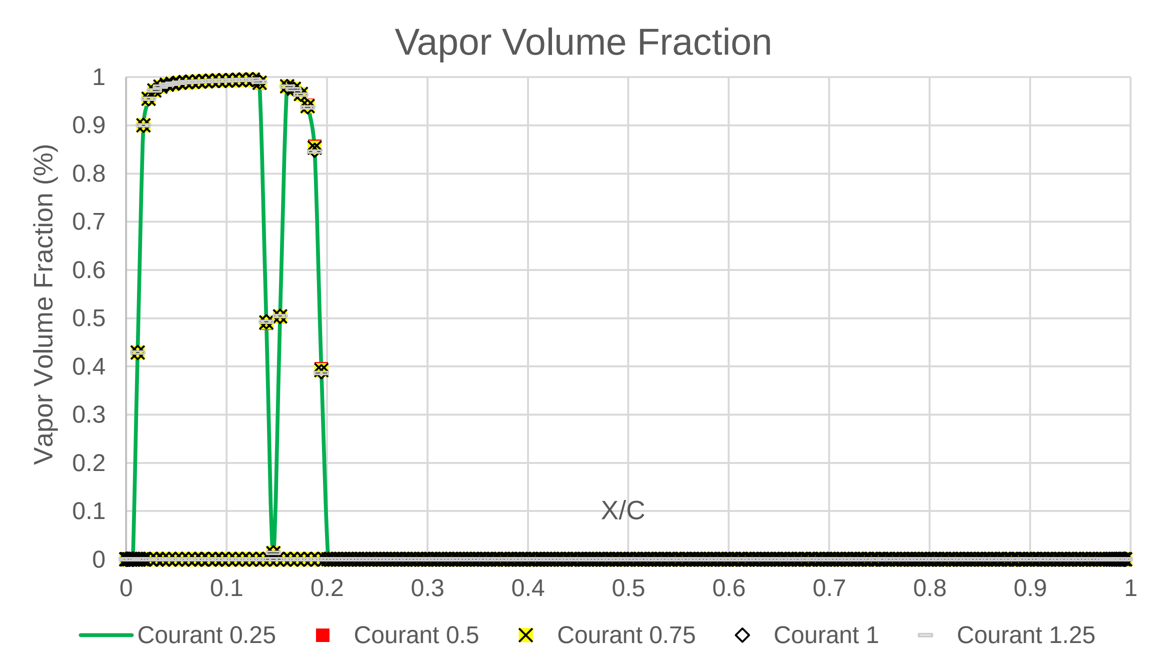


Time Step Investigation

- V=6 m/s
- 100 Inner Iterations
- Δx=1.4 mm (for the course mesh)
- Courant Number $C_u = \frac{v\Delta t}{\Delta\chi}$

Courant Number	Timestep
1.25	2.92E-04
1.0	2.34E-04
0.75	1.75E-04
0.5	1.17E-04
0.25	5.83E-05





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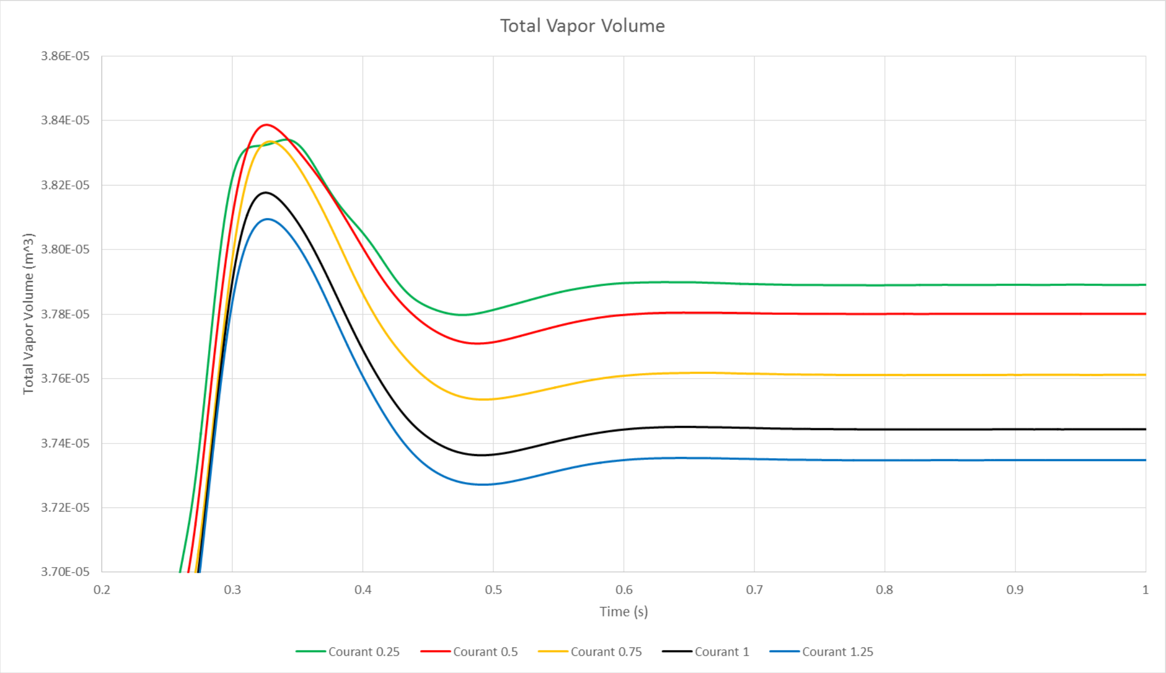
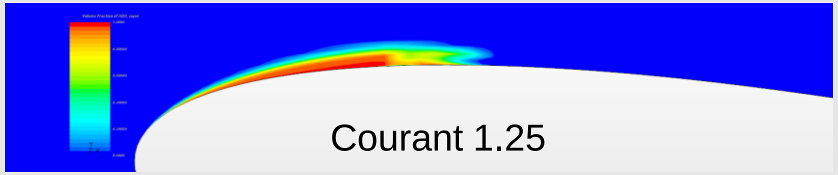
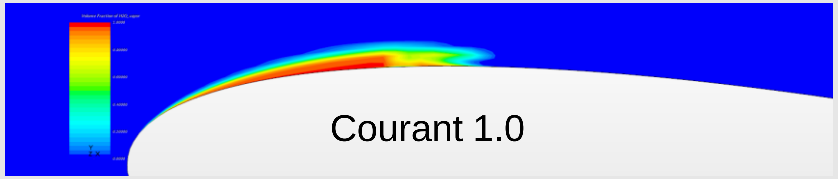
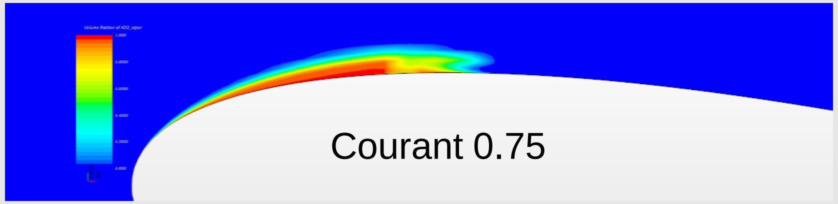
RESULTS – NACA 0015

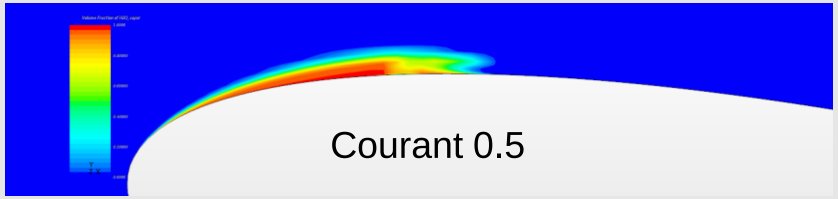
Courant Number	CD	CL	Vcav
1.25	0.01916	0.63491	3.7348E-05
1.0	0.01916	0.63500	3.7443E-05
Deviation (%)	0.0%	0.014%	0.255%
0.75	0.01916	0.63516	3.7612E-05
Deviation (%)	0.0%	0.025%	0.448%
0.5	0.01917	0.63537	3.7802E-05
Deviation (%)	0.052%	0.033%	0.502%
0.25	0.01917	0.63571	3.7891E-05
Deviation (%)	0.0%	0.053%	0.237%

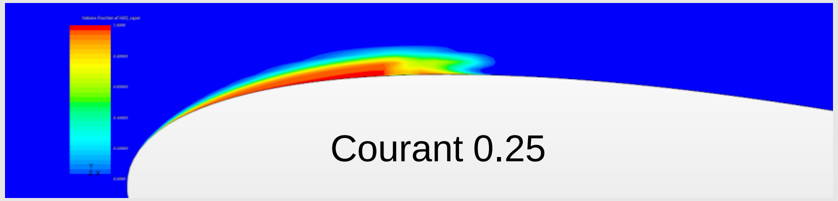






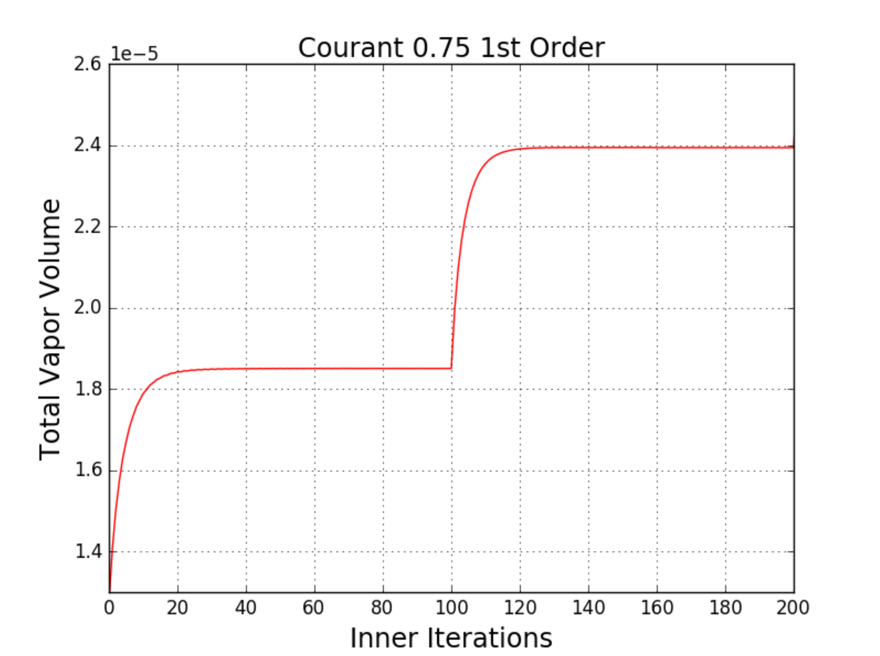


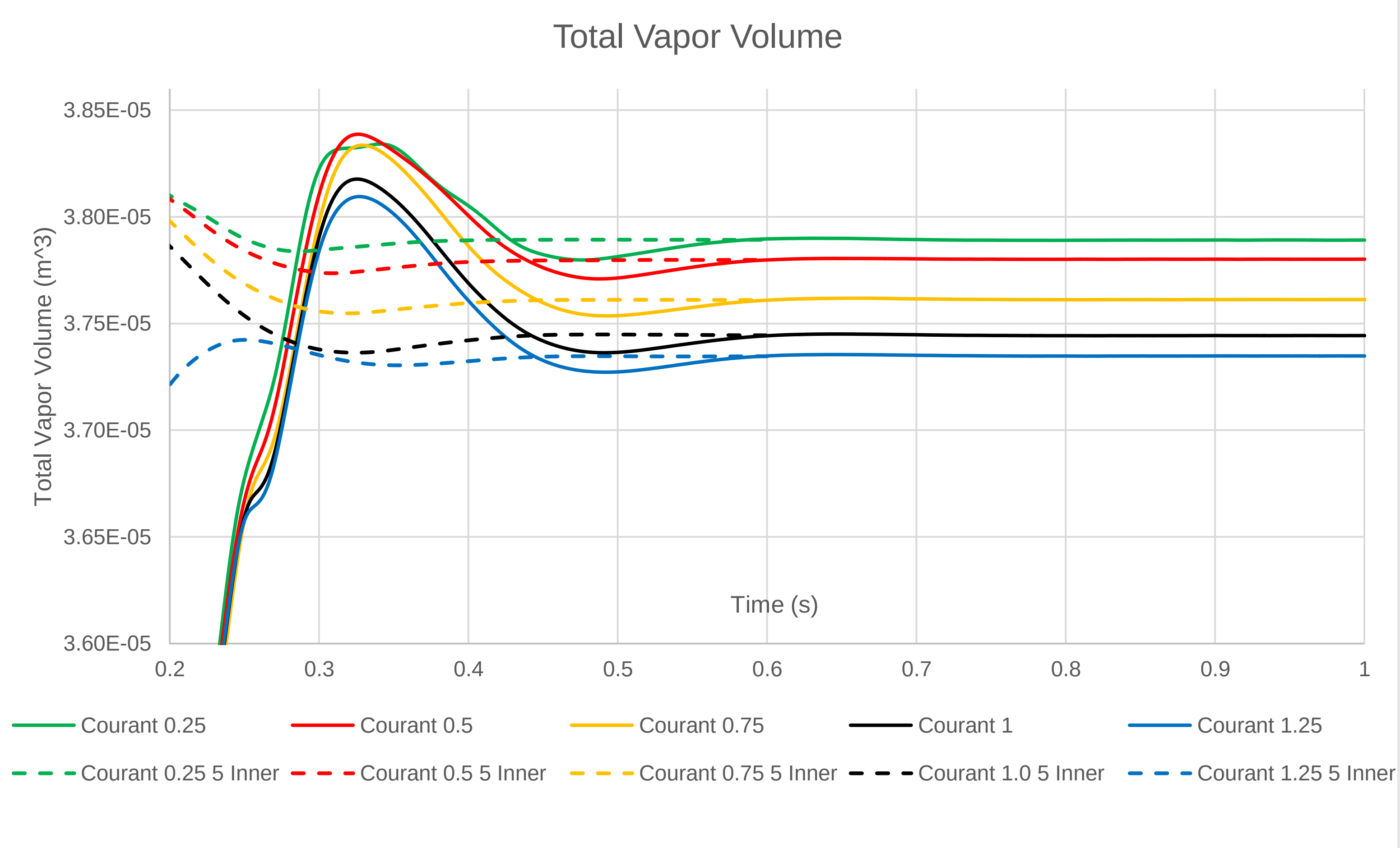




Inner Iterations Investigation

- TVV : convergence after 30 iterations per time step
- Identical results even with 5 iterations per time step





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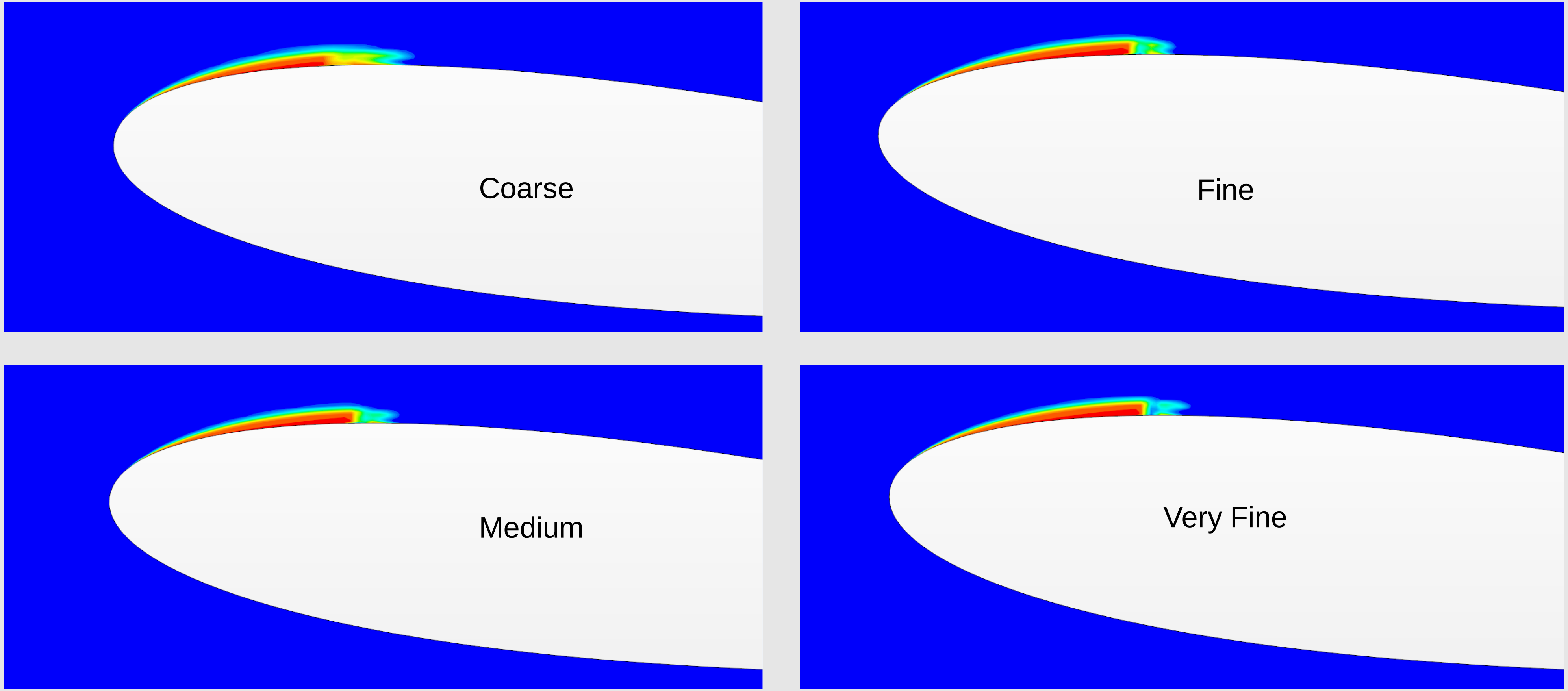
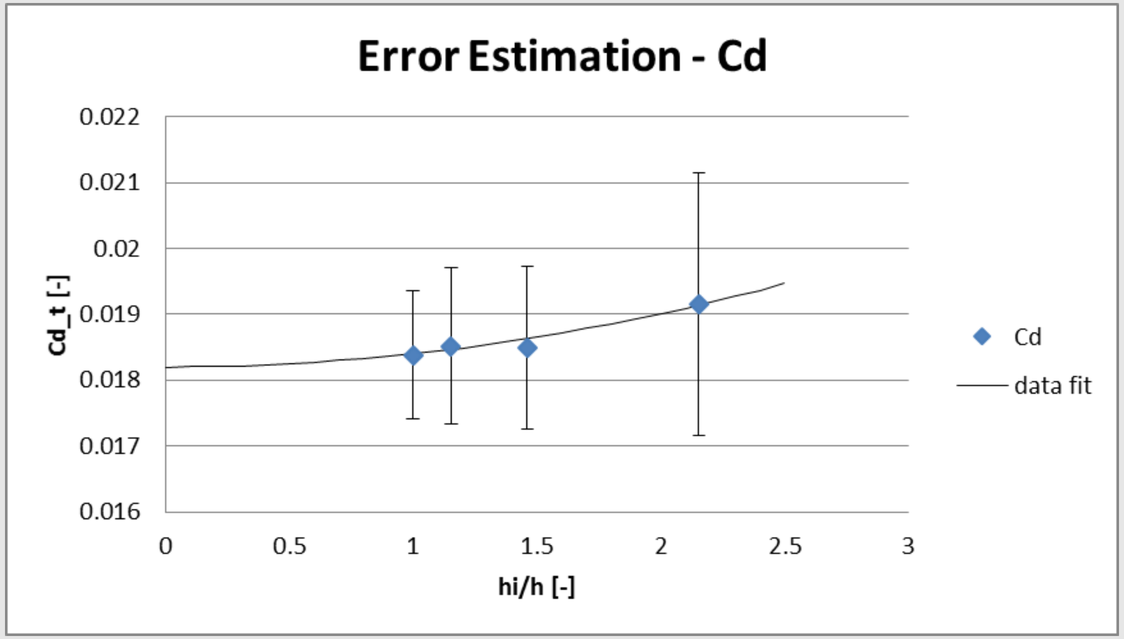
Vapor Volume Fraction for different grid density

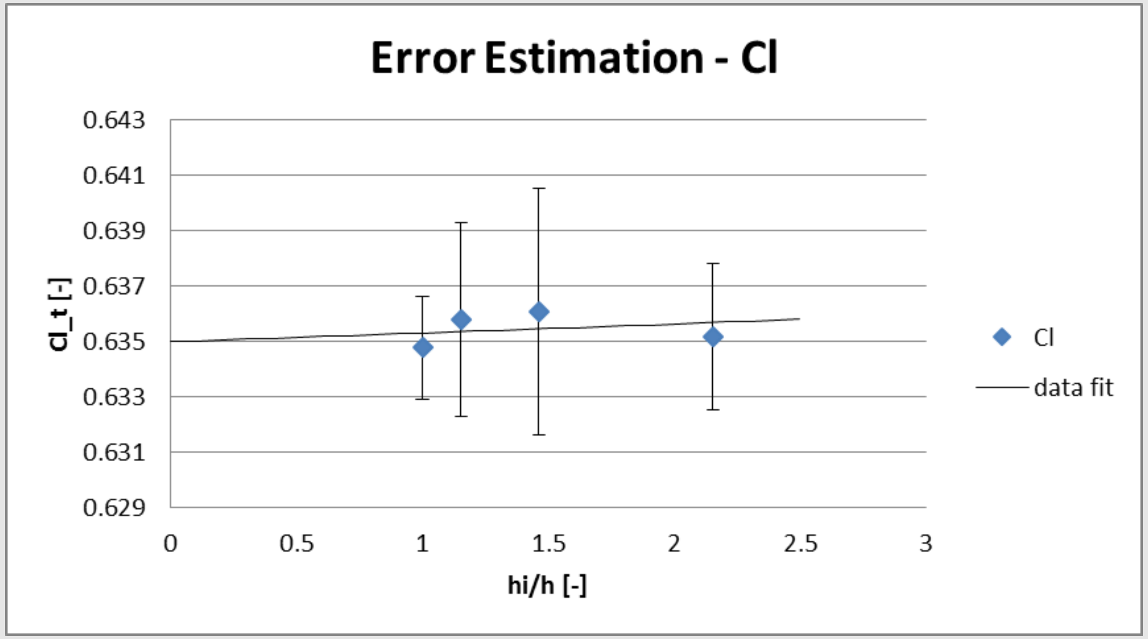


The grid density has a slight impact on the shape of the sheet cavity

Assessment of Uncertainty

Mesh	Cd	Uncertainty	Cl	Uncertainty
Coarse	0.01916	15.67%	0.6352	0.24%
Medium	0.01849	6.02%	0.6361	0.68%
Fine	0.01852	6.00%	0.6358	0.51%
Very Fine	0.01838	3.61%	0.6348	0.35%



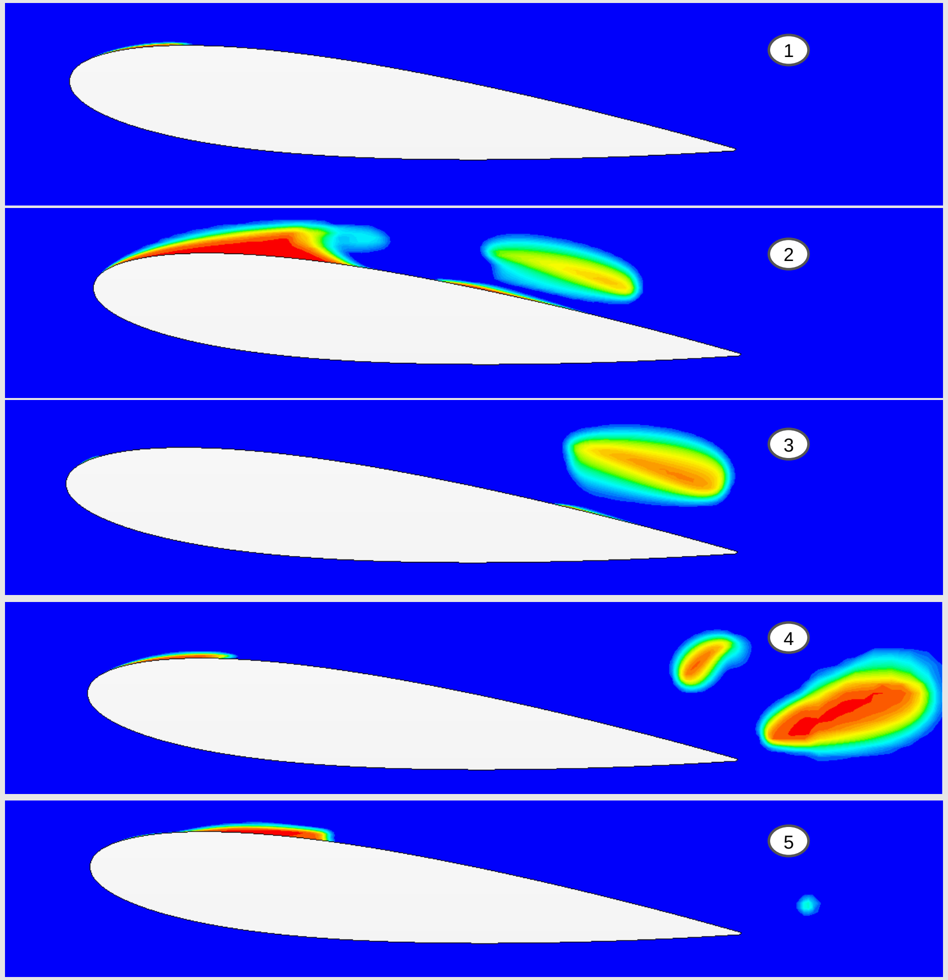


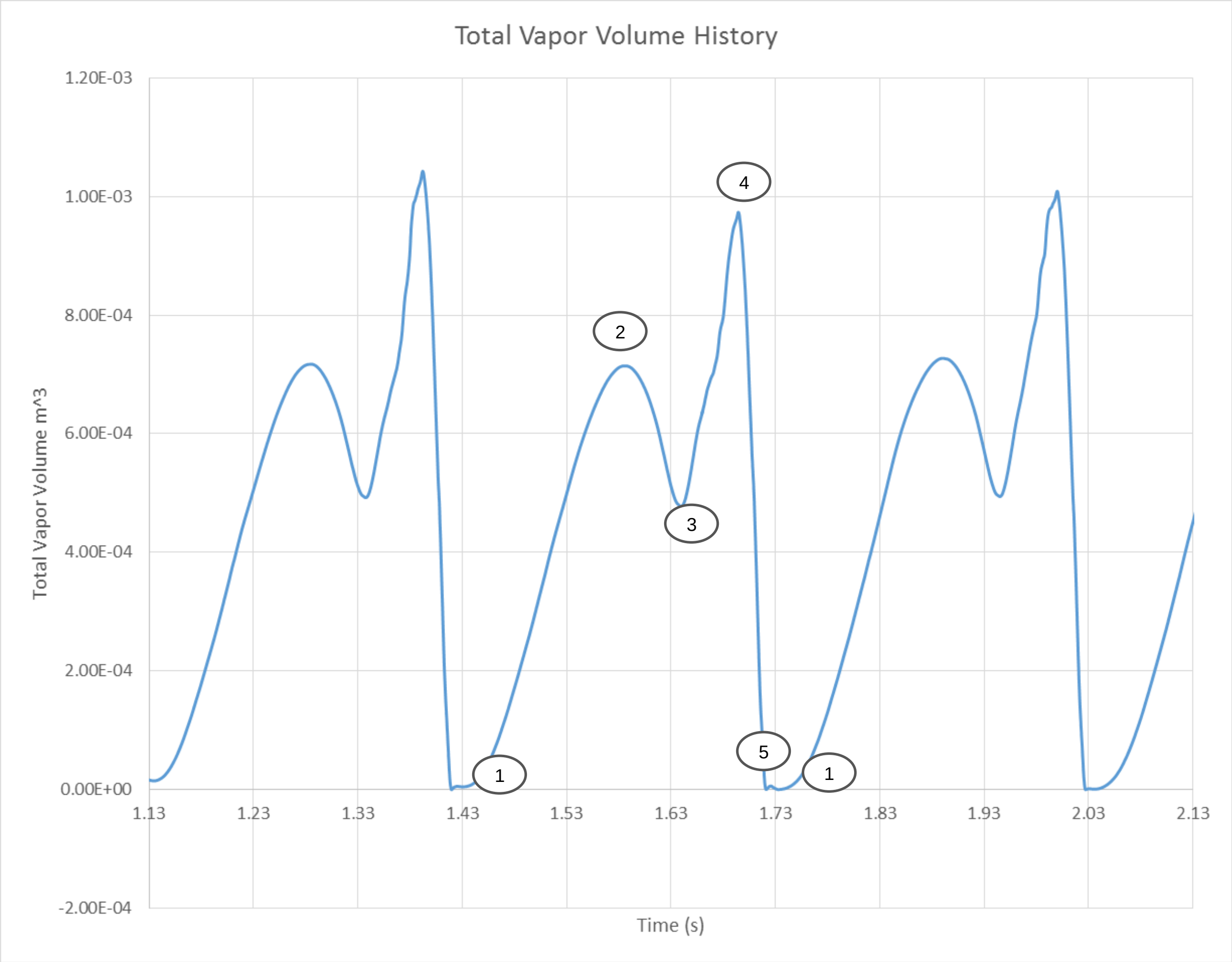
RESULTS – NACA 0015

CAVITATING FLOW

Cavitation Number 1.0

Typical Shedding Cycle (Courant Number 0.75)

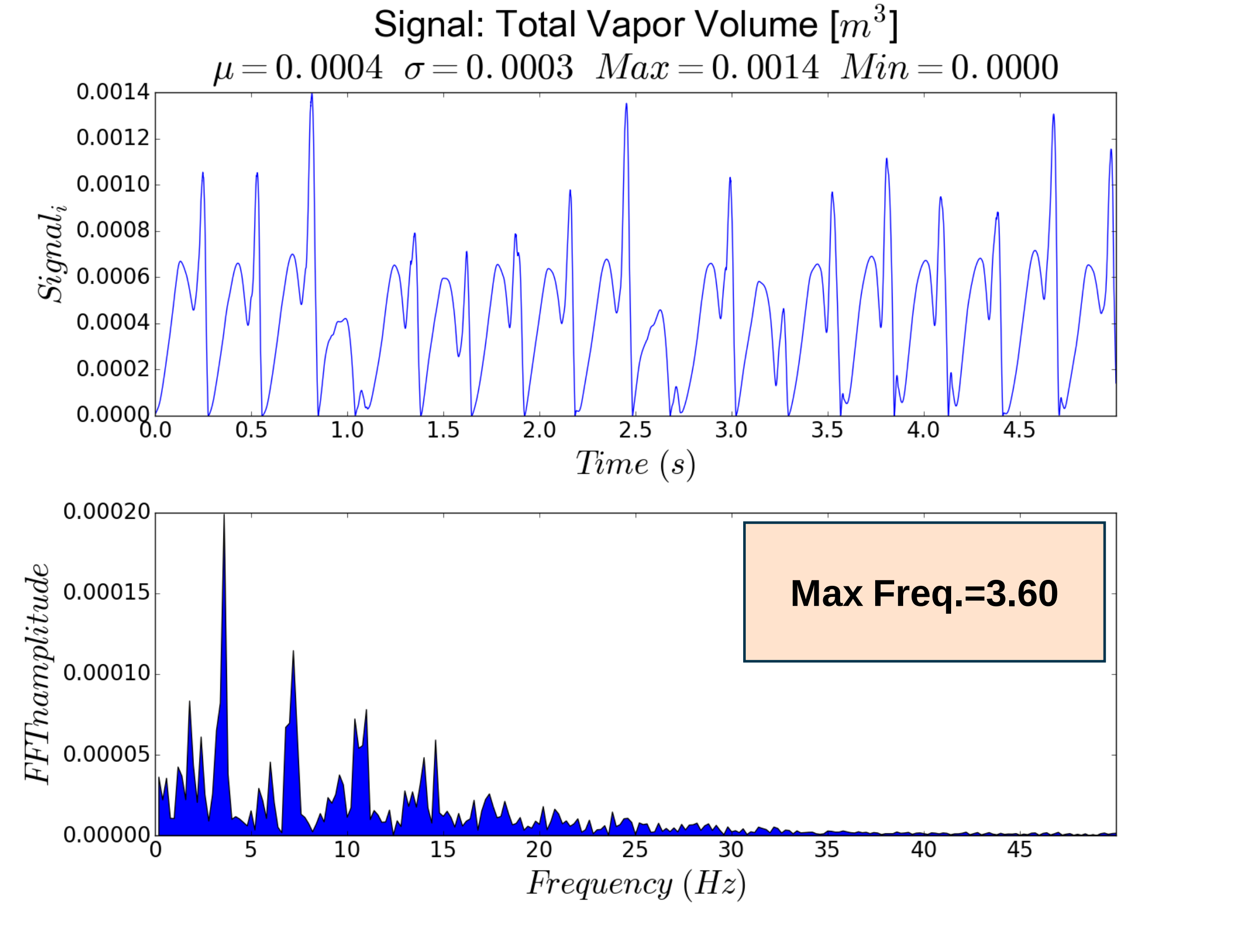




[A Numerical Study on the Shedding Frequency of Sheet Cavitation / Melissaris, Bulten and Terwisga]

Spectral Analysis of the Total Vapor Volume

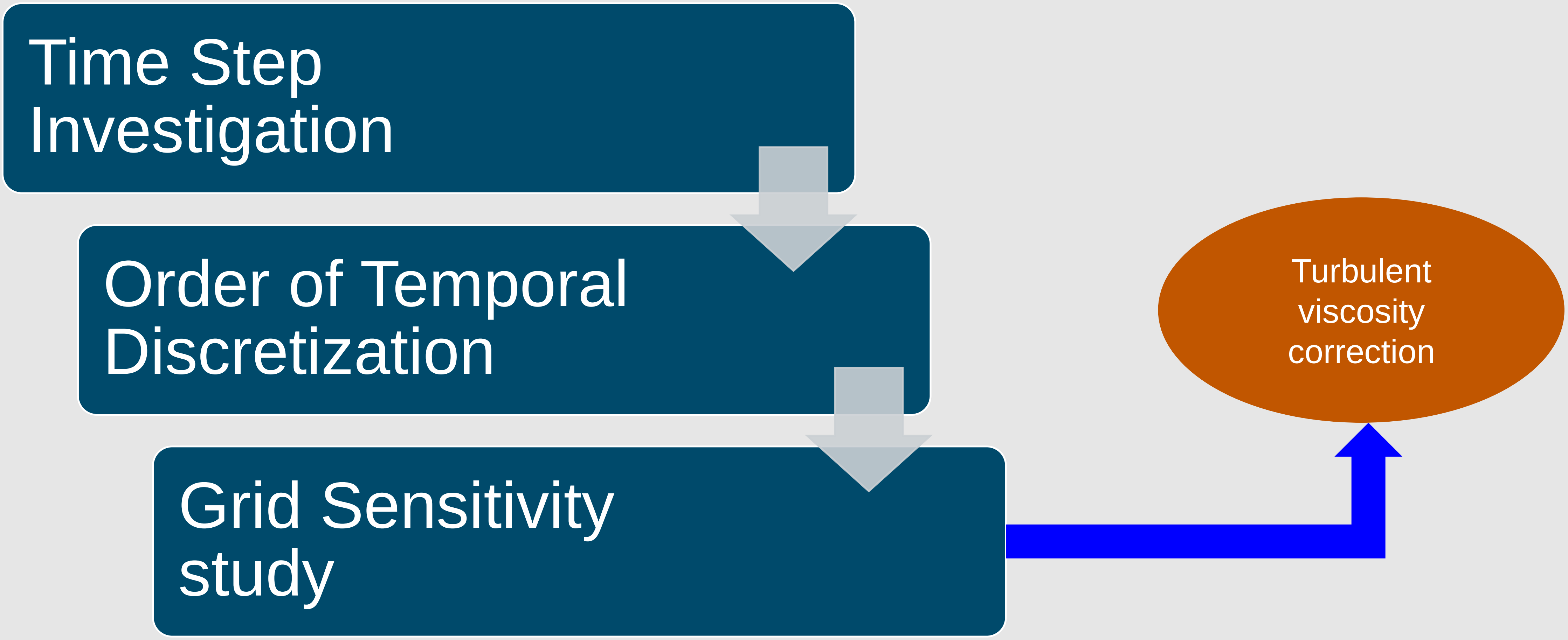
- FFT Analysis over 18 cycles
- First harmonic frequency at 3.6 Hz



Other numerical studies

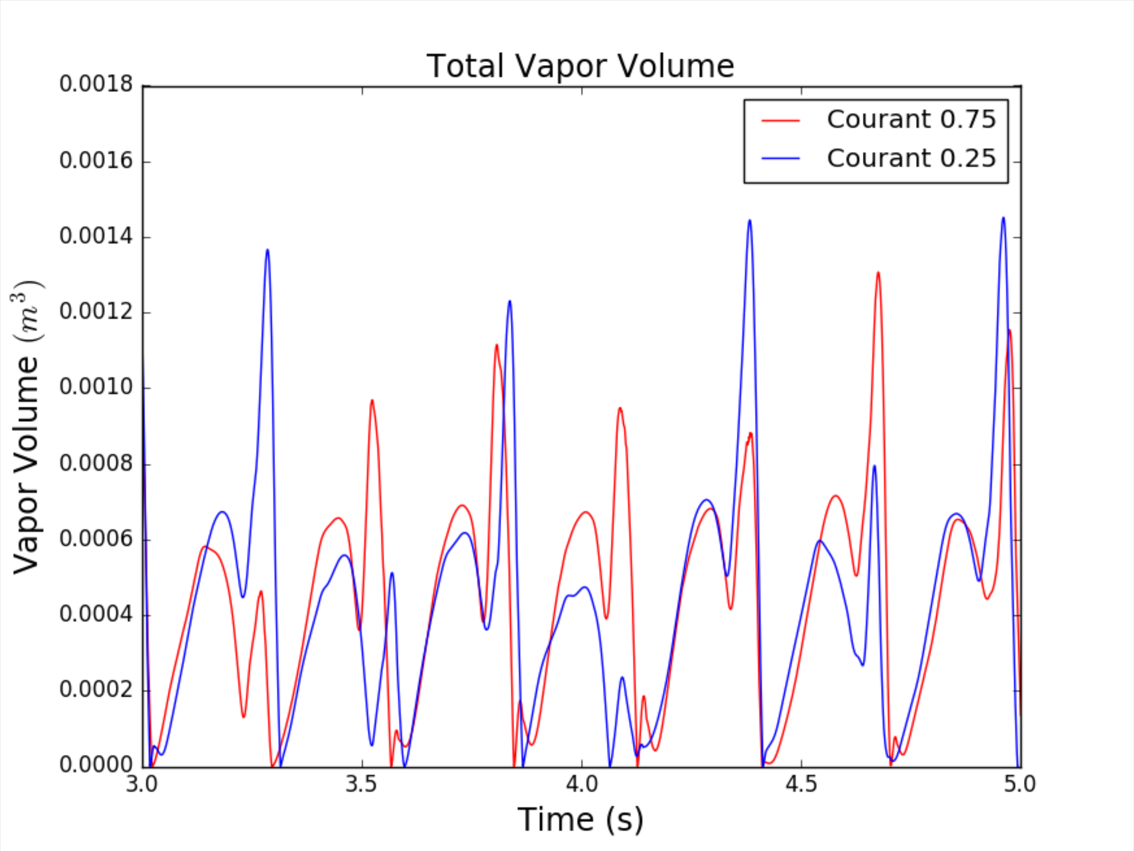
Authors	Frequency (Hz)
Sauer	11
Schnerr	11.18
Koop	24
Oprea	14
Hoekstra	15.4
Li	11

[A Numerical Study on the Shedding Frequency of Sheet Cavitation / Melissaris, Bulten and Terwisga]

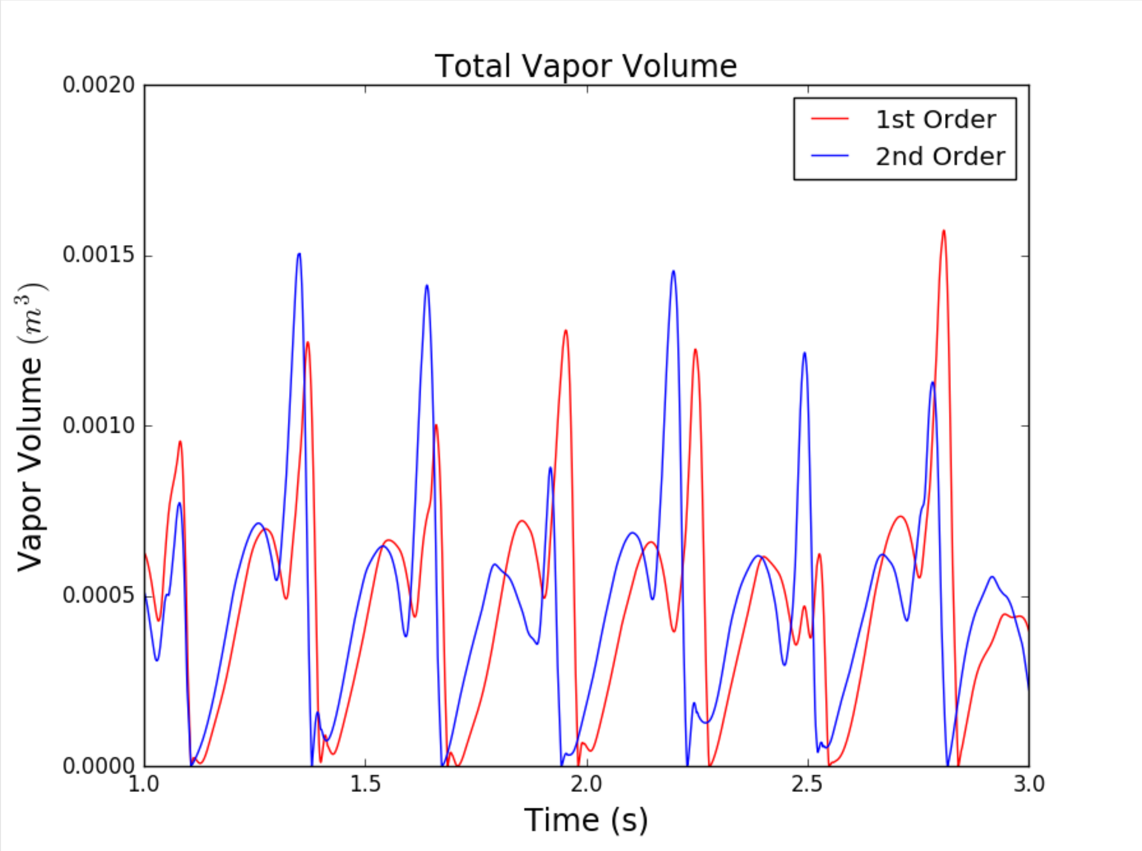

Time Step Investigation
Order of Temporal Discretization
Grid Sensitivity study
Turbulent viscosity correction

Comparison between different time steps and discretization schemes

Time Step



Discretization Scheme



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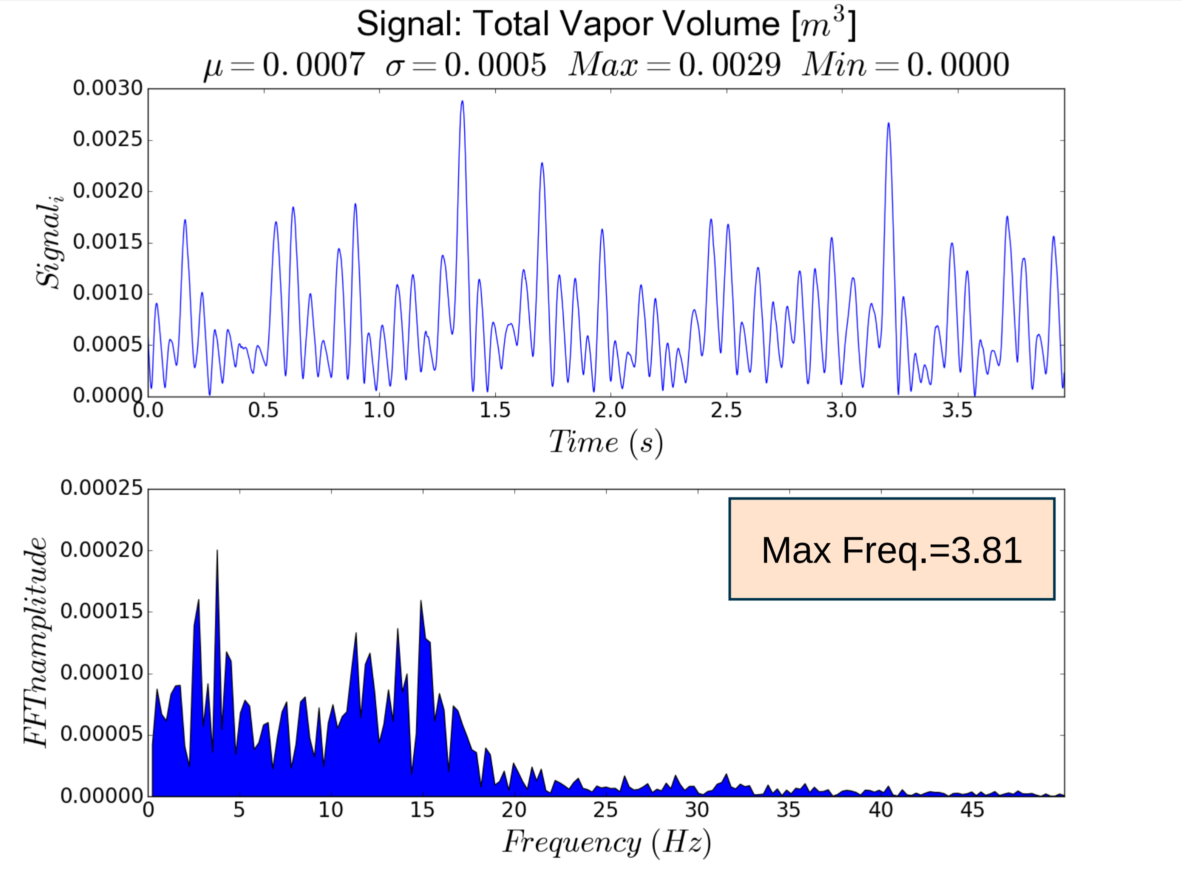
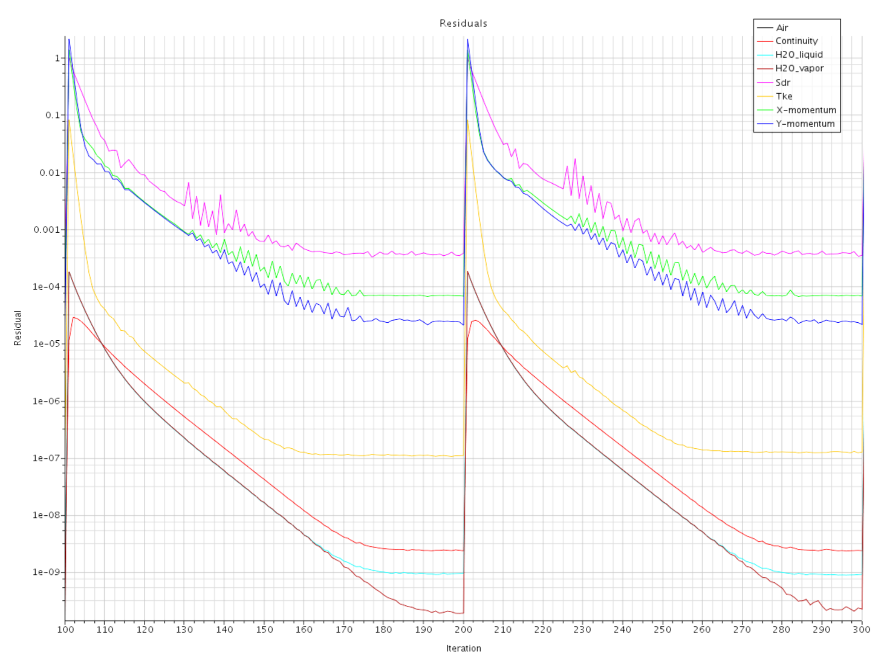
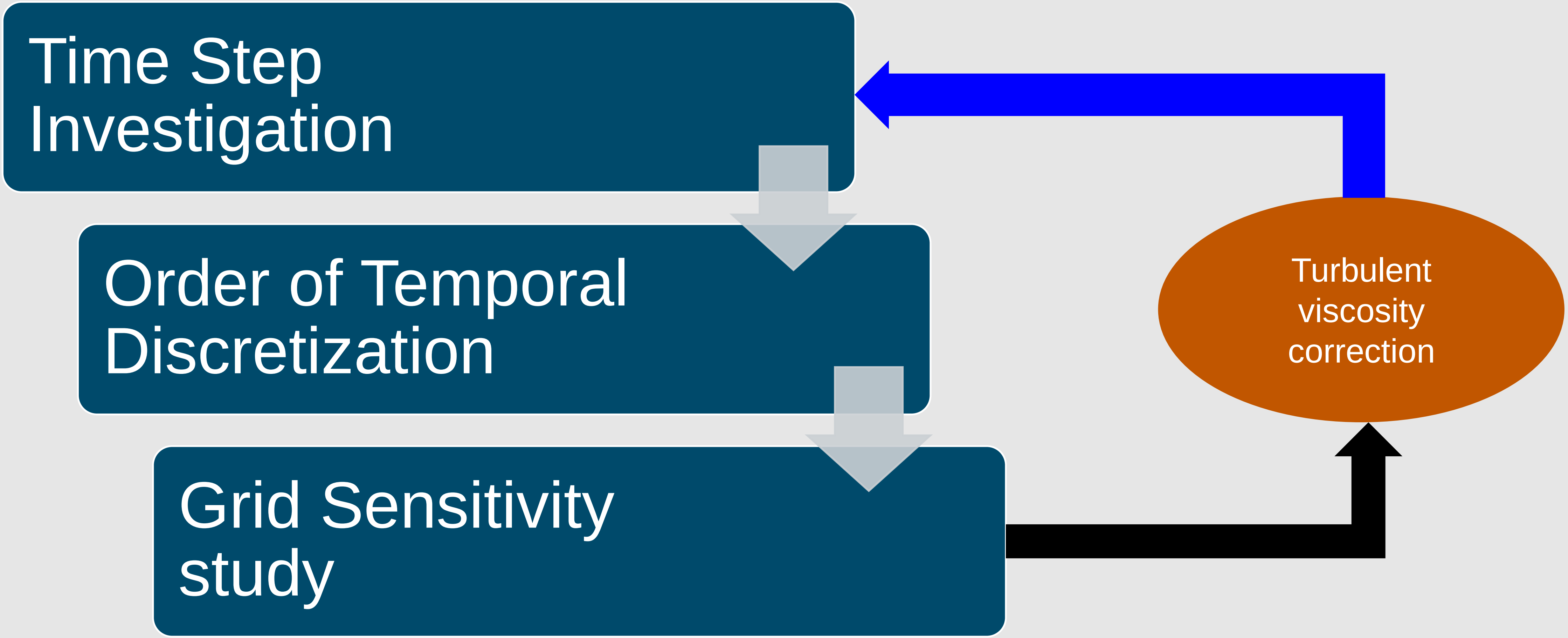
Results with correction for turbulent viscosity (Reboud *et. al.*)

- $\mu_t = f(\rho) C_\omega \frac{k}{\omega}; \quad f(\rho) = \rho_v + \frac{(\rho_m - \rho_v)^n}{(\rho_l - \rho_v)^{n-1}}; \quad n \gg 1$
- Reduces the turbulent viscosity on the cavity wake





[A Numerical Study on the Shedding Frequency of Sheet Cavitation / Melissaris, Bulten and Terwisga]


Time Step Investigation
Order of Temporal Discretization
Grid Sensitivity study
Turbulent viscosity correction

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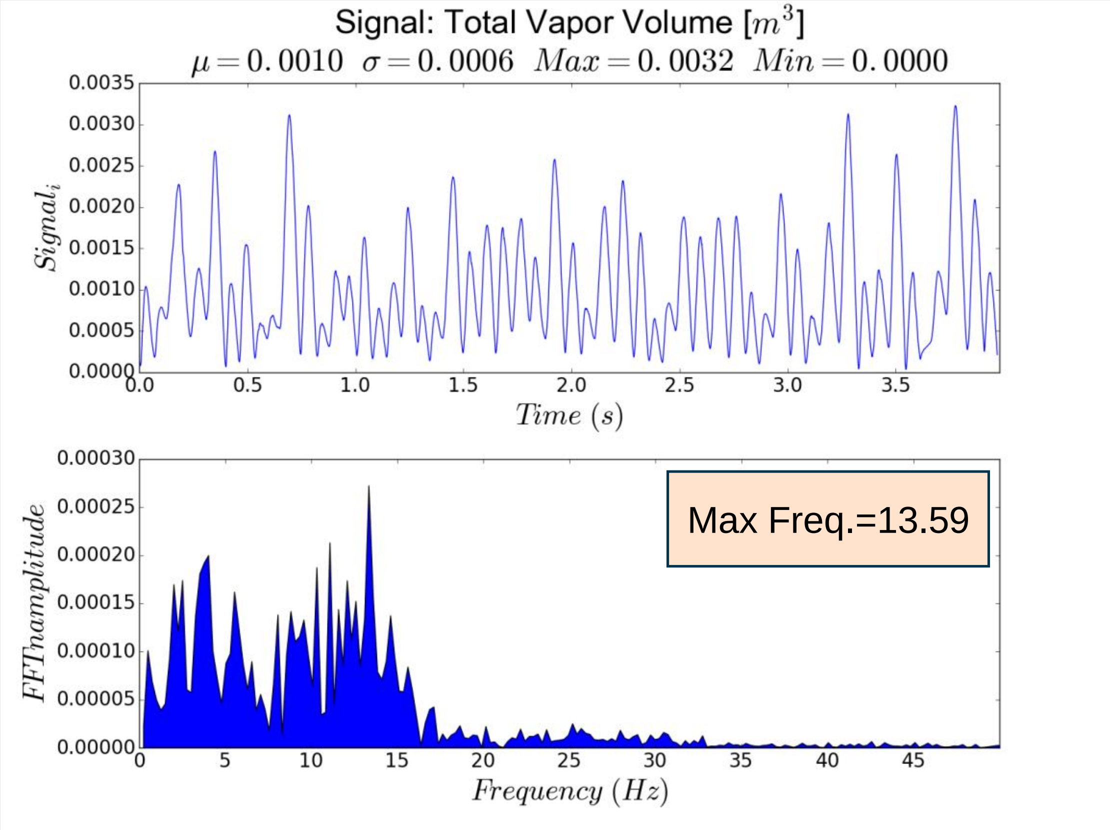
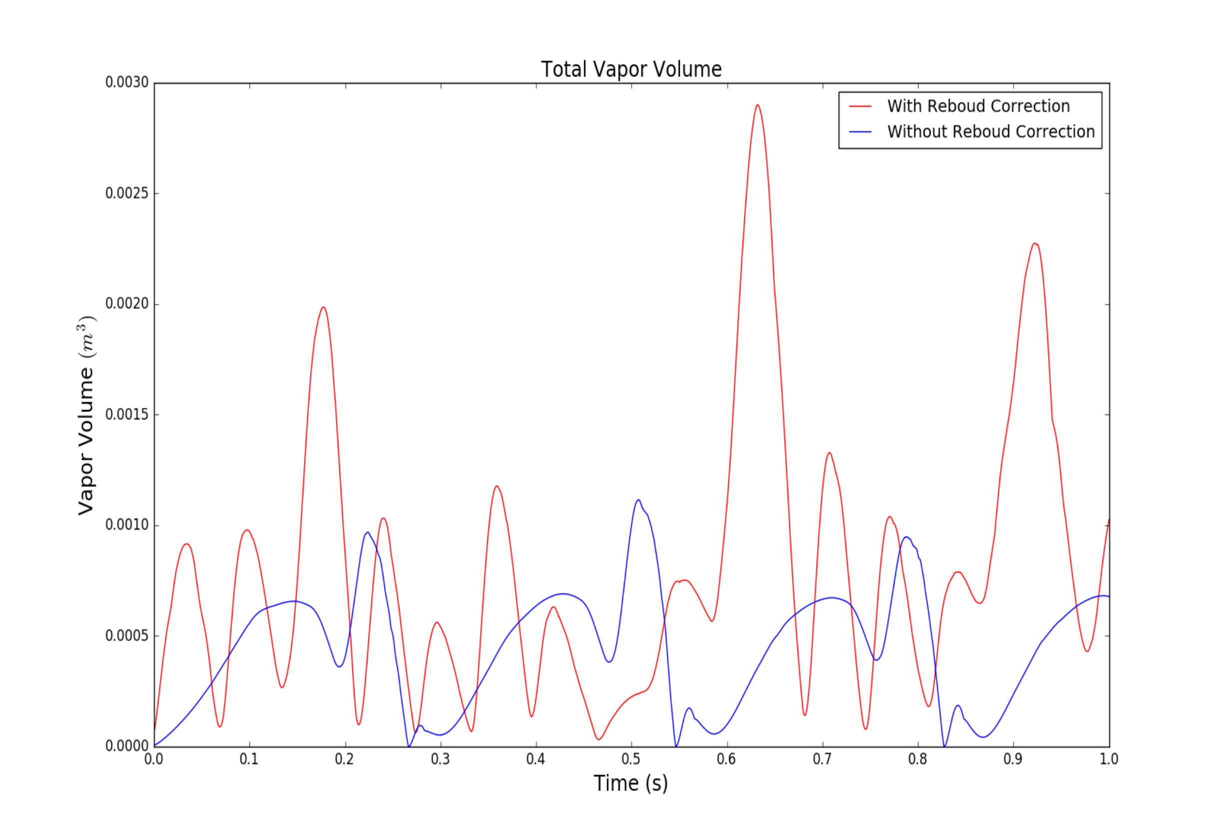
Results with Reboud correction and 2nd order discretization scheme

- FFT Analysis over 4 seconds ~ 50 cycles
- Highest harmonic frequency at 13.59 Hz

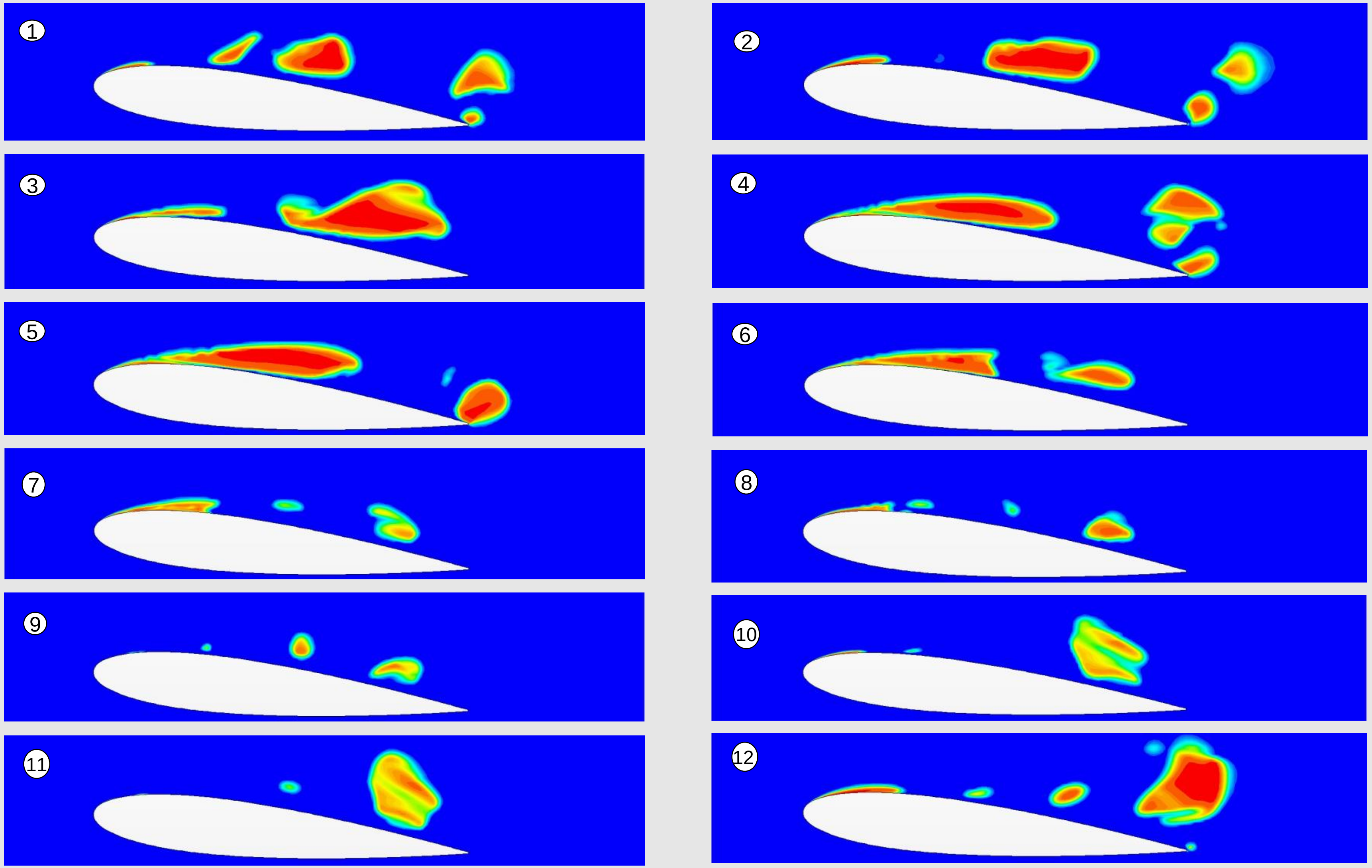




Results with Reboud correction and different grid densities

Grid density	Shedding (Hz)	Uncertainty(U_φ)
G1 (Coarse)	13.59	15.40%
G2 (Medium)	13.92	22.44%
G3 (Fine)	13.50	12.32%
G4 (Very Fine)	13.23	7.39%

Typical shedding cycle with viscosity correction



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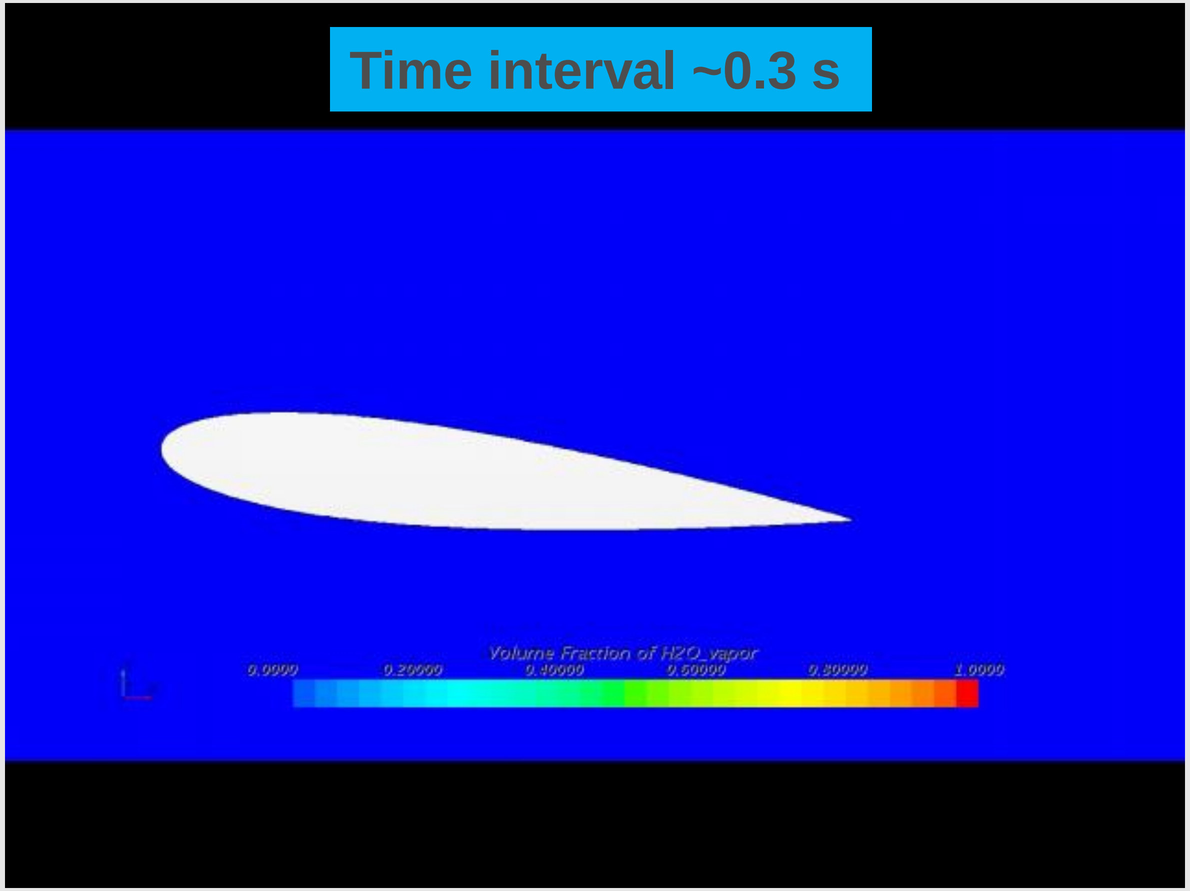
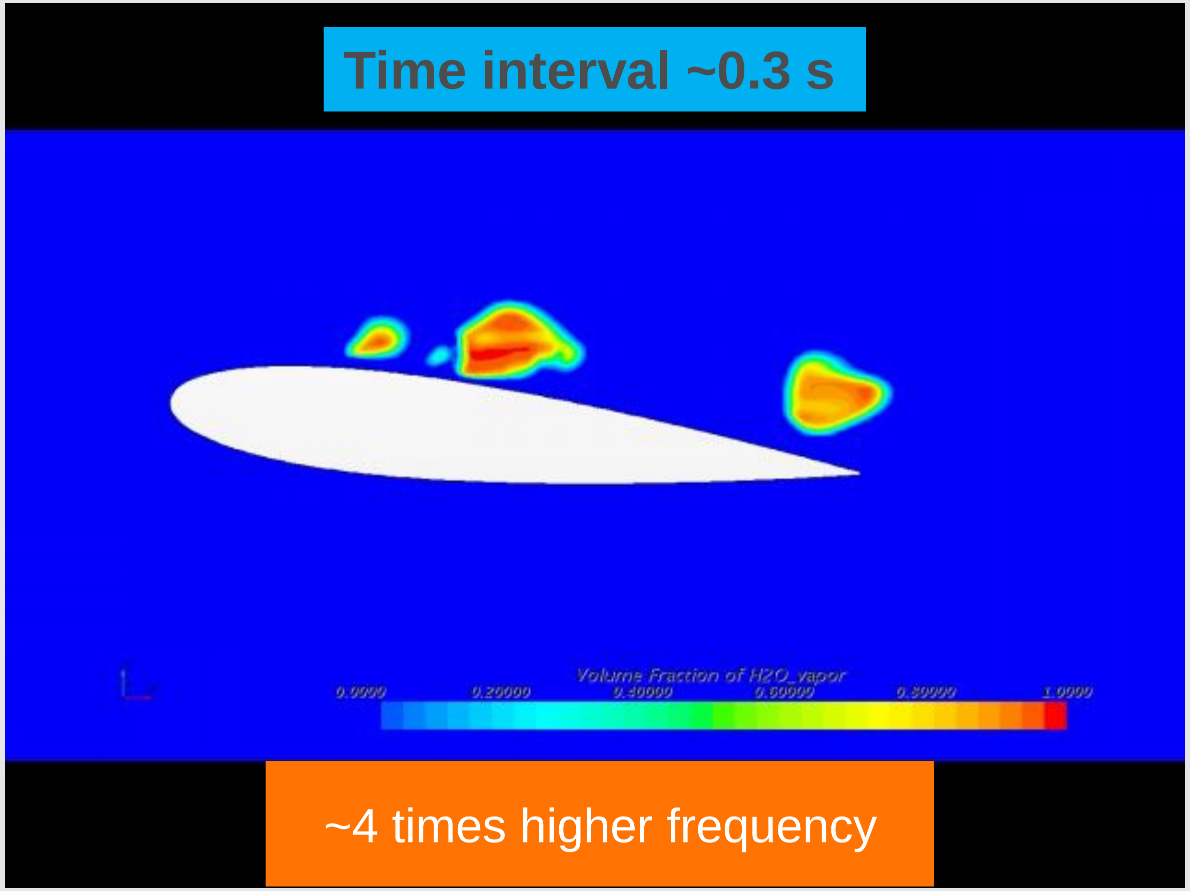
Visualization of the typical cycle with and without the Reboud correction

Without Reboud Correction



With Reboud Correction



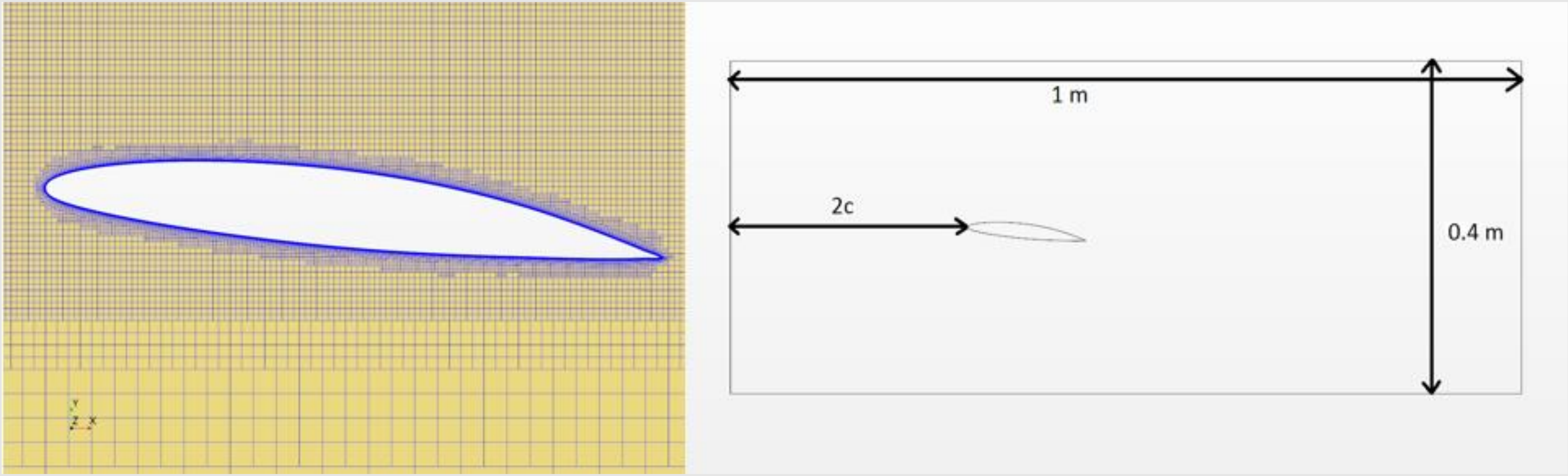
[A Numerical Study on the Shedding Frequency of Sheet Cavitation / Melissaris, Bulten and Terwisga]

CASE DESCRIPTION

NACA 66(mod)-312 a=0.8

Case Description

- $\tau = 12\%$ at 45% from LE
- 2% camber at 50% from LE
- Experimental comparison with results from Leroux et. al. 2005



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Computational Setup

Boundary conditions	NACA 66 (mod.) – 312	
Velocity Inlet	Vin = 5.33 m/s	
Angle of incidence	6 degrees	8 degrees
Pressure Outlet	Pout = 16.5kPa (σ=1.0)	Pout = 20.5 kPa (σ=1.28)
Turbulent Intensity	1%	
Turbulent Viscosity Ratio	10	
Foil	No-slip Wall	
Top	Slip Wall	
Bottom	Slip Wall	

Fluid Properties	Liquid	Vapor
Density	ρ = 998.2 $\mathrm{kg/m^3}$	ρ = 0.0177 $\mathrm{kg/m^3}$
Dynamic Viscosity	μ = 0.001002 kg/ms	μ = 1×10^{-5} kg/ms
Saturation Pressure	p_v =2338 Pa	-

RESULTS – NACA 66

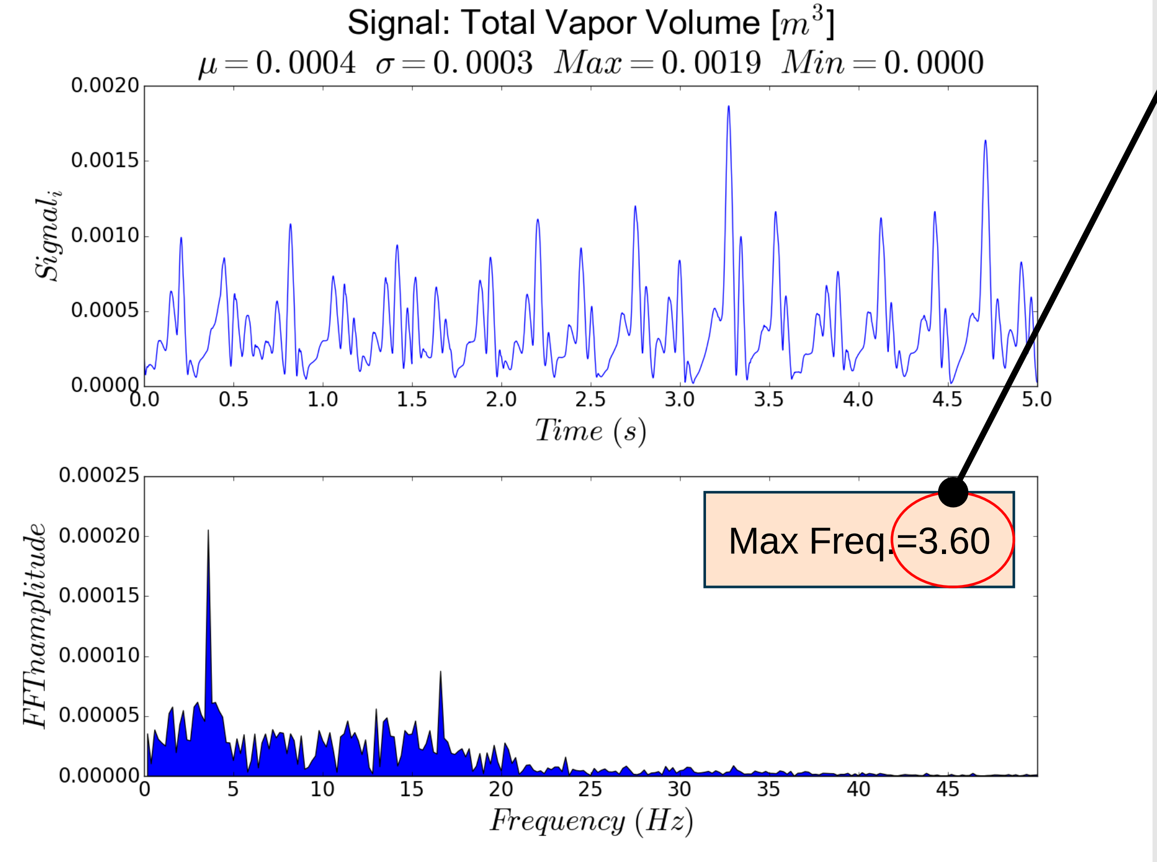
CAVITATING FLOW

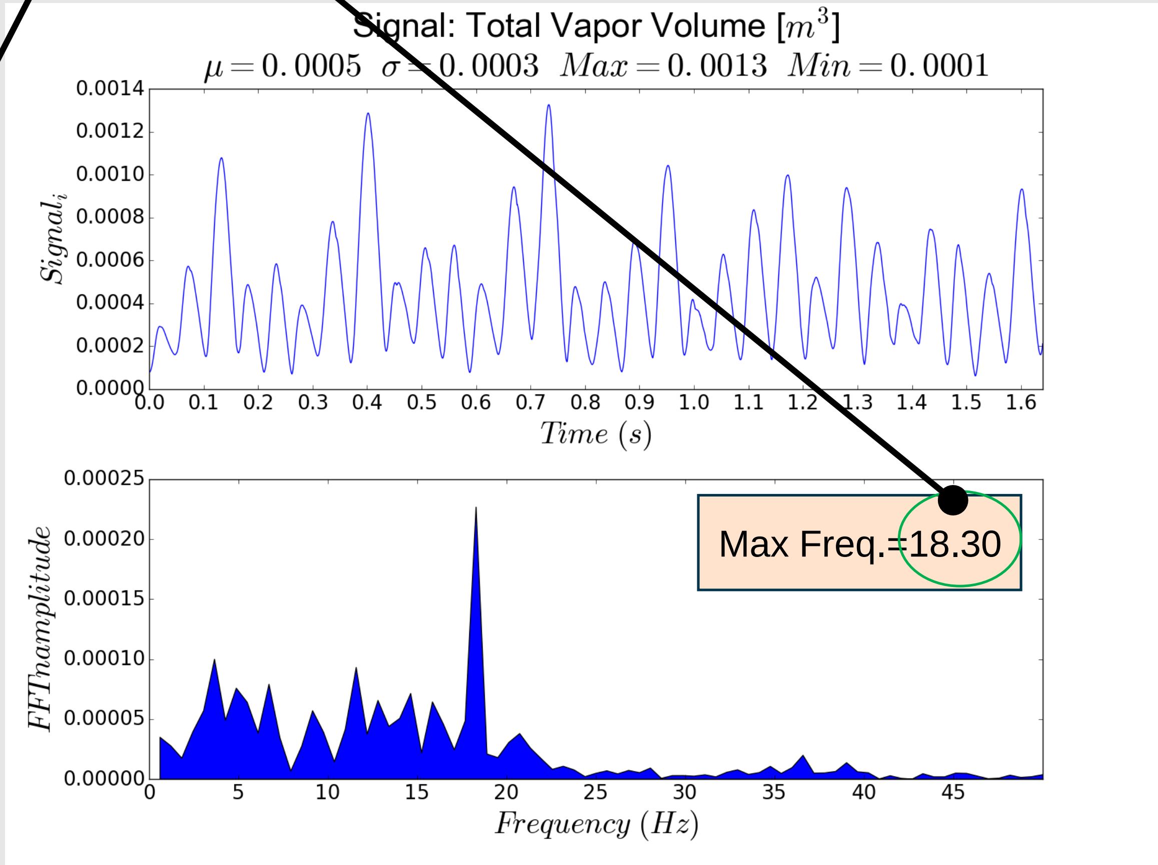
Spectral Analysis

- Velocity Inlet 5.33 m/s
- Angle of incidence 6 and 8 degrees
- Comparison with experimental results from Leroux et. al.

TABLE I. Experimental frequency of cavity oscillation as a function of the angle of incidence and Strouhal numbers based on chord length or cavity length when defined. V_{ref}=5.33 m/s, Re=0.8×10^6, $\Delta\sigma=\pm0.02$.

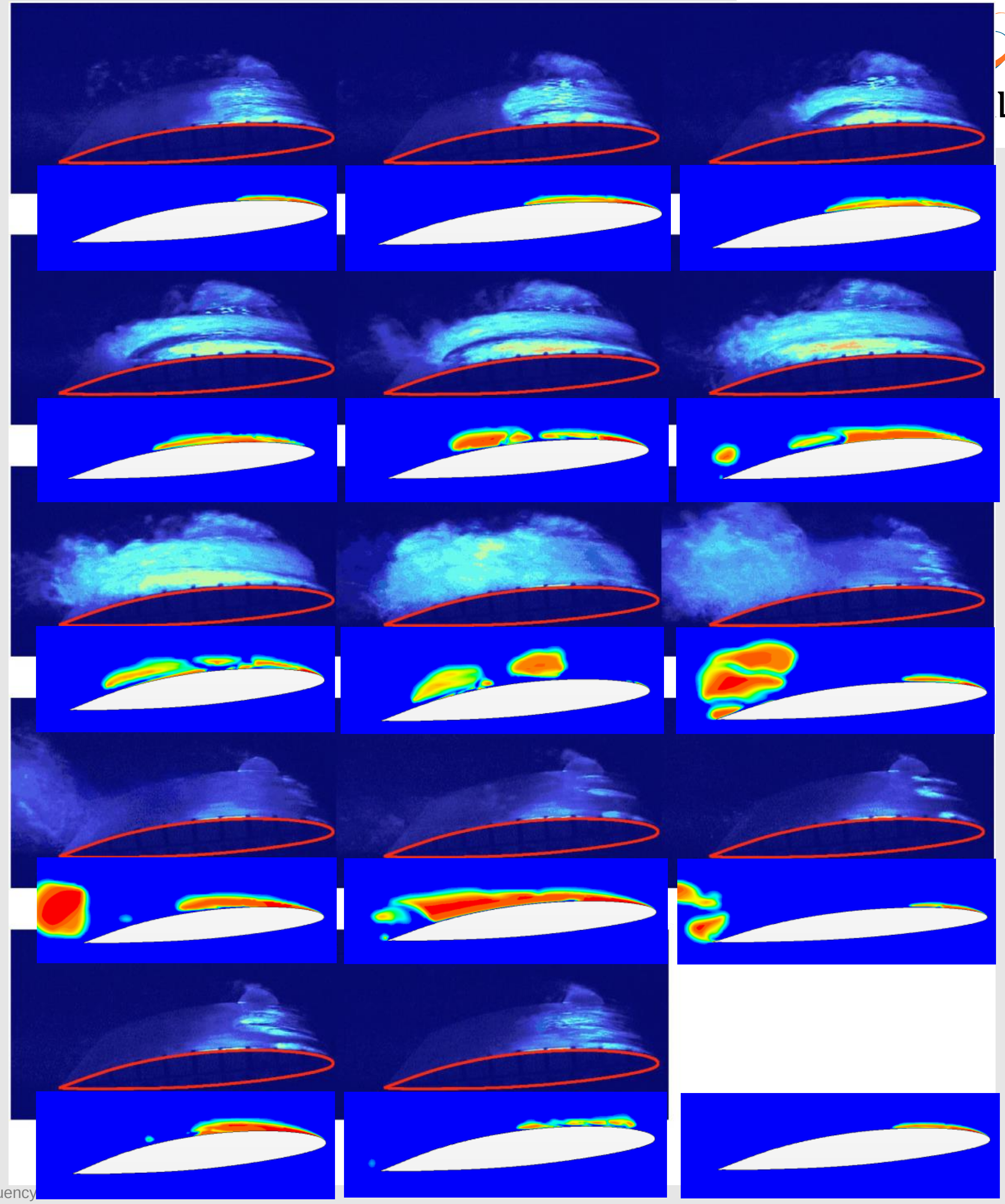
α(deg)	f(Hz)	σ	$\sigma/2(\alpha-\alpha_0)$	st_c	st_l
5.5	2.88	0.88	3.193	0.081	Nondefined
6.0	3.50	1.00	3.431	0.098	Nondefined
7.0	4.50	1.13	3.447	0.127	Nondefined
8.0	18.00	1.28	3.529	0.507	0.304





Experimental – Numerical Comparison

- **Experiment:**
  - α = 6 deg
  - σ = 0.99
  - St_c = 1.10
  - V = 5.33 m/s
  - Δt = 1/50
- **Computation:**
  - α = 6 deg
  - σ = 1.0
  - St_c = 1.10
  - V = 5.33 m/s
  - Δt = 1/50



[A Numerical Study on the Shedding Frequency Cavitation / Melissaris, Bulten and Terwisga]

CONCLUSIONS

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Wetted Flow

- Good prediction of the wetted flow characteristics using the k-ω SST turbulence model

Cavitating Flow (cn = 1.6)

- A steady sheet cavity is predicted of about 20% of the chord length
- The effect of the time step and the number of the inner iteration on the results are negligible
- The grid density had a slight impact on the shape of the sheet cavity

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Cavitating Flow (cn = 1.0)

- The time step, the number of inner iterations per time step and the order of temporal discretization seem to play an important role on the prediction of the shedding frequency
- It is suggested that they are selected in such a way that convergence of the total vapor volume per time step is achieved
- A higher frequency was captured only when the correction for the turbulence viscosity in areas with higher vapor volume was applied
- A grid independent solution has been reached; even the coarsest mesh was capable of capturing the dynamic shedding in a high frequency after application of Reboud's eddy viscosity correction

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Cavitating Flow

- Good agreement with the experiments was obtained and the shedding frequency was accurately predicted
- Discrepancies can only be observed in the maximum total volume per cycle

THANK YOU FOR YOUR ATTENTION

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